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SYMPOSIUM ON TELEVISION

A GROUP OF FIVE PAPERS
DESCRIBING THE APPARATUS AND METHODS
USED IN THE EXPERIMENTAL DEMONSTRATION OF TELEVISION
OVER COMMUNICATION CHANNELS OF THE
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Symposium on Television

Television.....*Herbert E. Ives*

The Production and Utilization of Television Signals.....*Frank Gray, J. W. Horton, R. C. Mathes*

Synchronization of Television.....*H. M. Stoller, E. R. Morton*

Wire Transmission System for Television.....*D. K. Gannett, E. I. Green*

Radio Transmission System for Television....*Edward L. Nelson*

Television [1]

By HERBERT E. IVES

Bell Telephone Laboratories, Incorporated

SYNOPSIS: The chief problems presented in the accomplishment of television are discussed. These are: the resolution of the scene into a series of electrical signals of adequate intensity for transmission; the provision of a transmission channel capable of transmitting a wide band of frequencies without distortion; means for utilizing the transmitted signals to re-create the image in a form suitable for viewing by one or more observers; arrangements for the accurate synchronization of the apparatus at the two ends of the transmission channel.

INTRODUCTION

THIS paper is to serve as an introduction to the group of papers following, which describe the apparatus and methods used in the recent experimental demonstration of television over communication channels of the Bell System. In that demonstration television was shown both by wire and by radio. The wire demonstration consisted in the transmission of images from Washington, D. C., to the auditorium of the Bell Telephone Laboratories in New York, a distance of over 250 miles by wire. In the radio demonstration, images were transmitted from the Bell Laboratories experimental station at Whippany, New Jersey, to New York City, a distance of 22 miles. Reception was by two forms of apparatus. In one, a small image approximately 2 in. by 2½ in. was produced, suitable for viewing by a single person, in the other a large image, approximately 2 ft. by 2½ ft., was produced, for viewing by an audience of considerable size. The smaller form of apparatus was primarily intended as an adjunct to the telephone, and by its means individuals in New York were enabled to see their friends in Washington with whom they carried on telephone conversations. The larger form of receiving apparatus was designed to serve as a visual adjunct to a public address system. Images of speakers in Washington addressing remarks intended for an entire audience, and of singers and other entertainers at Whippany, were seen by its use, simultaneously with the reproduction of their voices by loud speaking equipment.

[1] Presented at the Summer Convention of the A. I. E. E., Detroit, Mich., June 20–24, 1927.

Characteristic Problems of Television

The problem of television in its broad outlines is that of converting light signals into electrical signals, transmitting these signals to a distance, and then converting the electrical signals back into light signals. Given means for accomplishing these three essential tasks, the problem becomes that of developing these means to the requisite degree of sensitiveness, speed, efficiency, and accuracy, in order to re-create a changing scene at a distant point, without appreciable lapse of time, in a form satisfactory to the eye.

A convenient starting point for the discussion of television is the human eye itself. In this an image is formed upon the retina, a sensitive screen, consisting of a multitude of individual light-sensitive elements. Each of these elements is the termination of a nerve fibre which goes directly to the brain, the entire group of many million fibres constituting the optic nerve. A theoretically possible television system could be made by copying the eye. Thus a large number of photosensitive elements could be connected each with an individual transmission channel leading to a distant point, and signals could be sent simultaneously from each of the sensitive elements to be simultaneously used for the re-creation of the image at the distant point. The number of wires or other communication channels demanded in a television system of this sort would be impractically large. For practical purposes, reduction of the number of transmission channels is made possible by the fact that, while in vision all parts of the image on the retina are simultaneously and continuously acting to send nerve impulses, the inertia of the visual system is such that a sensation of continuity is obtained from discontinuous signals, provided these succeed each other rapidly enough. Due to the phenomenon of persistence of vision, it is immaterial to the eye whether the whole view be presented simultaneously or whether its various elements be viewed in succession, provided the entire image be traversed in a sufficiently brief interval, which for purposes of discussion may be taken as 1/16th of a second or less.[2] We thus have available in television the same artifice which is used in the much less exacting problem of transmission of pictures over a telephone line, that is, of *scanning*, or running over the elements of the image in sequence, instead of endeavoring to transmit all of the elementary signals simultaneously. The development of a television system therefore

[2] This figure of 1/16th of a second, commonly quoted in discussions of this sort, is a convenient one, although the frequency of image repetition necessary to extinguish "flicker" is actually proportional to the logarithm of the field brightness. A somewhat higher rate of image repetition was used in the final television apparatus.

necessitates, at an early stage, the design of some scanning system by which the image to be transmitted may be broken up into sequences of signals. In the simplest case, where one transmission channel is to be used, the whole image will be resolved into a single series of signals; if more than one transmission channel is to be utilized, the resolution may, by parallel scanning schemes, or their equivalent, be broken up into several series for simultaneous transmission.

Like the eye, an artificial television system must have some light-sensitive element or elements by means of which the light from the object shall produce signals of the sort which can be transmitted by the transmission system to be used. For a television system to operate over electrical transmission lines this means some photoelectric device. It is obvious that this photoelectric device must be extremely rapid in its response, since the number of elements of any image to be transmitted must be some large multiple of the fundamental image repetition frequency, that is 16 per second. The response should, of course, be proportional to the intensity of the light, and finally, the device must be sufficiently sensitive so that it will give an electrical signal of manageable size with the amount of light available through the scanning system. This latter requirement, that of sensitiveness, is one which, it was realized, from studies made with our earlier apparatus for the transmission of still pictures over wires,[3] would be extremely difficult to meet. In the picture transmission system a very intense beam of light from a small aperture is projected through a transparent film and on to a photoelectric cell. In practical television, the system must be arranged to handle light reflected from a natural object, under an illumination which would not be harmful or uncomfortable to a human being. Actual experiment showed that the greatest amount of light which could be collected from an image, formed by a large aperture photographic lens on the small scanning aperture of the picture transmission apparatus, was less by a factor of several thousand times than the light projected through it for still picture transmission purposes. Assuming the same kind of photoelectric cell to be used, the additional amplification required over that used in the picture transmission system, taking into account also the higher speed of response demanded, would bring us at once into the region where amplifier tube noise and other sources of interference would seriously affect the result. This indicated clearly that some more efficient method of gathering light from the object than the commonly assumed one of image formation by a

[3] "Transmission of Pictures over Telephone Lines," Ives, Horton, Parker and Clark. *Bell System Technical Journal*, Vol. IV, No. 2, April, 1925.

lens was required, unless some much more sensitive type of photoelectric cell should be found.

Assuming that means could be developed for producing an electrical signal proportional to the intensity of the light, of sufficient quickness to follow a rapid scanning device, and of sufficient strength either as directly delivered from a photosensitive device or as amplified, the next problem is that of its transmission over an electrical communication system. We may quickly arrive at an understanding of certain of the transmission problems by reviewing the requirements for the transmission of photographs. In the system of still picture transmission now in use by the American Telephone & Telegraph Company, a picture 5 in. by 7 in. in size, divided into the equivalent of 10,000 elements per square inch or 350,000 elements, is transmitted in approximately seven minutes. This requires the transmission of a frequency band of about 400 cycles per second on each side of the carrier frequency. If we plan, in the transmission of television, to transmit images of the same fineness of grain, it would mean that what is now transmitted in seven minutes would have to be transmitted in a 16th of a second, which in turn means that the transmission frequency range would have to be nearly 7000 times as great. That is, a band approximately 3,000,000 cycles wide would be required. Bearing in mind that wire circuits are ordinarily not designed to utilize frequencies higher than 40,000 cycles per second, and that with radio systems uniform transmission of wide signal bands becomes extremely difficult, it is seen at once that either an image of considerably less detail than that which we have been considering must suffice, or else some means for splitting up the image so that it may be sent by a large number of channels is indicated.

A further theoretical requirement must also be given consideration. This is that the complete television signal will consist of all frequencies up to the highest above discussed, and down to zero, that is, an essential part of the signal is the direct current component, furnished by those parts of the scene which do not change. The problem of handling the very low frequency components, presents difficulties both in the vacuum tube amplifier system adjacent to the photosensitive device, and in ordinarily available transmission channels.

In any case certain fundamental transmission requirements must be met. These are that the attenuation of the signals must be uniform over the whole frequency range and that the speed of transmission of all frequencies must be the same. Also, as in the transmission of sound signals, the amount of interference or noise must be kept down sufficiently not to impair the quality of the signal or picture.

Assuming the undistorted transmission of the signals to a distant point, the next fundamental problem of television is the reconstruction of the image, or the translation of the electrical signal back into light of varying intensity. Just as at the sending end we have seen that the production of a useful electrical signal with the amount of light available from a naturally illuminated object is a major problem, so at the receiving end the converse problem, that of securing an adequately bright light from the electrical signal, presents great difficulty. The nature of the problem may be understood by assuming that it is to be done by projecting the received image on a screen similar to an optical lantern projection screen. If the spot of light which is to build up this image scans the whole area in the same way that the object is scanned, we find that the amount of light which can be concentrated into a small elementary spot will, when distributed by the scanning operation over the whole screen, reduce the brightness of the screen in the ratio of the relative areas of the elementary spot and the whole screen. The amount of this reduction will, of course, depend upon the number of elements into which the picture is divided, but will in any event be a factor of several thousand times. It is doubtful whether any light source exists of sufficient intensity such that an image projected by it can be spread out by a scanning operation over a large screen and give an average screen brightness which would be at all adequate. It is possible to imagine optical systems by which such a thing as the crater of an arc could be projected upon the screen, but the motion of this image and its variation in intensity would involve the extremely rapid motion of lenses, mirrors and apertures of a size such as to render the operation mechanically impracticable. It appears from these considerations that the only promising means of reconstructing the image would be those in which a light source, whose intensity can be controlled with great rapidity, is directly viewed.

Another element of a television system upon whose solution success depends as much as any other is that of synchronization; the reconstruction of the image, postulated in the last paragraph, is only possible if the reconstructed elements fall in exactly the right positions at the right times, to correspond with the signals as generated at the analyzing end. The criterion for satisfactory synchronization will be expressed in terms of variation from identity of speed by figures which will depend on the fineness of grain of the image which it is planned to send. No element of the image must, of course, be out of place by a considerable fraction of the size of the element.

General Outline of Means Employed in the Present Television System

It has been pointed out above that if the goal which we set in television is the transmission of extended scenes, with a large amount of detail and hence made up of an exceedingly large number of elementary areas, we meet with the necessity for transmission channels of a character which are not now available. In the present development it was decided at the start to restrict our experiments to a size and grain of picture which, if the scanning and re-creating means were developed, would be capable of transmission over practical transmission channels, either wire or radio. This restriction fortunately leaves us with the possibility of meeting what was felt to be the typical problem of a Telephone Company, namely, the transmission of a human face in a television system used as an adjunct to a telephone system. Taking, as a criterion of acceptable quality, reproduction by the halftone engraving process, it is known that the human face can be satisfactorily reproduced by a 50-line screen. Assuming equal definition in both directions, 50 lines means 2500 elementary areas in all. 2500 elements transmitted in 1/16 second is 40,000 elements per second. The frequency range necessary to transmit this number of elements per second with a fidelity satisfactory for television cannot be calculated with assurance in advance. An approximate value can however be arrived at from a study of the results obtained in still picture transmission. In pictures transmitted by the system already referred to, individual faces contained in a square space ½ inch on a side are quite recognizable.[4] Taking the ratio of this area to the area of the whole picture, and using the frequency range figure already deduced, for a complete 5 in. by 7 in. picture, it appears that a band of 20,000 cycles would be sufficient to transmit such an image in 1/16 second.[5] These considerations led to the choice of a 50-line (2500-element) image as one which would be both satisfactory as to detail rendering, for our purposes, and as calling for frequency transmission requirements sufficiently low to give a good margin of safety in existing single communication channels.

As a method of scanning, the method which is probably mechanically simplest, namely, that of rotating disks with spirally arranged holes, proposed by Plotnow[6] in 1884, was chosen. In accordance with the

[4] Cf. Fig. 18 of the paper referred to (Reference 2).

[5] A factor which this analogy does not cover is that if the image is moving so that it falls on several discrete scanning elements in rapid succession a very material apparent increase in the fineness of the image structure results. This effect is similar to that by which the relatively coarse-grained individual images in a motion picture film fuse to give smooth appearing pictures.

[6] Plotnow, D. R. P. 30105, 6.1, 1884.

choice of grain above indicated, the disks were perforated with 50 apertures.

For the second element of the problem, the light-sensitive means, the alkali metal photoelectric cell was chosen as possessing the qualities of proportionality of response and quickness of reaction. The currents produced by it are at best quite small, but they lend themselves to the process of amplification by the three-electrode vacuum tube amplifier.

The problem of securing a large enough signal, which is intimately associated with that of securing enough light from the object, was, in our development work, postponed in the earlier stages, our first experimental work having been done by concentrating light through photographic transparencies.[7] The solution of the problem of securing adequate light was subsequently attained by reversing the light path and projecting a narrow beam of light through the scanning disk upon the object. By this means only the element of the object which was being scanned was illuminated at any one time, thereby reducing the average illumination enormously, and the problem of increasing the signal strength could be attacked by increasing the amount of photosensitive surface as well as by increasing the brightness of the scanning light.[8]

The problem of amplifying the photoelectric currents to sufficient value for transmission was solved by a practical compromise which at the same time met one of the transmission difficulties. This compromise consisted in amplifying and transmitting only the fluctuating or alternating current components of the signal, leaving the direct current component, which determines the general tone value of the image, for empirical reintroduction at the receiving end. By this scheme, stable amplifier constructions were made available, and the transmission channels, particularly the wire channels, could be utilized in their normal working form.

At the receiving end, the problem of securing a sufficiently bright image was solved, as indicated earlier, by the use of self-luminous surfaces of much higher intrinsic brightness than it is possible to secure by illumination of a surface by any light source which can be rapidly controlled as to its intensity. The self-luminous surfaces

[7] As one step in the development work moving picture film, projected by a commercial projector in synchronism with the scanning disks, was successfully transmitted.

[8] A still further advantage is obtained by limiting the scanning light to the region of the spectrum to which the photoelectric cells are sensitive (blue and violet). This is unnecessary where one-way transmission only is used but is of value where in two-way transmission a transmitted image is to be viewed by a person being scanned.

employed were glow lamps containing neon gas, the brightness of which changes with sufficient rapidity to follow the incoming signals.

The problem of synchronization was postponed in our earlier development work by mounting the scanning and receiving disks upon the same axle. It was later solved for the demonstration apparatus by the utilization of synchronous motors controlled by two frequencies, a low frequency, that of the image repetition period, and a high frequency, chosen of such a value that the fraction of the cycle through which transient phase displacements occurred amounted in angular displacement to less than half the angular extent of a single disk aperture. The synchronization control therefore called for the transmission of additional currents for synchronization purposes over and above the picture current.

In order to transmit and synchronize the image signals it is necessary to transmit three different frequency bands, one for the image, and two for the high and low frequency synchronization controls. In the demonstration of April 7, 1927, the images were sent in the wire demonstration over a high quality open wire line. The synchronization control was sent over two separate carrier channels of a second telephone line. In addition to these lines, another line was used for conveying the telephone conversation. In the radio demonstration two different wave-lengths were used respectively for the image signals and for the synchronization signals which were, as in the wire demonstration, carried on two different carrier frequencies. A third channel was used for the voice. In the case of both wire and radio transmission, it is quite possible to put all of the different signals upon the same transmission channel, using different carrier frequencies.

It will aid toward a clear understanding of the reasons for the success of the system of television described in the following papers if we summarize at this point the chief novel features to which that success is due. They may be listed as follows:

1. Choice of image size and structure such that the resultant signals fall within the transmission frequency range of available transmission channels.[9]

2. Scanning by means of a projected moving beam of light.

3. Transmission only of alternating current components of image.

4. Use of self-luminous surfaces of high intrinsic brilliancy for reconstruction of the image.

5. High frequency synchronization.

[9] As the succeeding papers show, the margin between the frequency range required by the scanning apparatus and that which could be made available was quite liberal. It appears in the light of our experience that apparatus with 60 or 70 scanning holes instead of 50 might be used with the transmission facilities which were at our disposal.

Applications and Future Developments

It is not easy at this early date to predict with any confidence what will be the first or the chief uses for television, or the exact lines that future development may take. It must be clearly understood that television will always be a more expensive service than telephony, for the fundamental reason that it demands many times the transmission channel capacity necessary for voice transmission. This expense will inevitably increase in proportion to the size and quality of the transmitted image.

The kinds of service which are naturally thought of upon consideration of the services now rendered in connection with sound transmission are: first, service from individual to individual, parallel in character to telephone service, and as an adjunct thereto; second, public address service, by which the face of a speaker at a distant point could be viewed by an audience while his voice was transmitted by loud speaker; third, the broadcasting of scenic events of public interest, such as athletic contests, theatrical performances and the like.

The first two types of service just mentioned lie within the range of physical practicability, with apparatus of the general type already developed. The third type, because of the uncontrolled conditions of illumination, and the much finer picture structure which would be necessary for satisfactory results, will require a very considerable advance in the sensitiveness and the efficiency of the apparatus, to say nothing of the greatly increased transmission facilities. For all three types of service, wire or radio transmission channels could be utilized, for while the problems incident to securing distortionless transmission over wide frequency bands, or multiple transmission channels, are different in detail in the two cases, they appear to be equally capable of solution by either means. However, the very serious degradation of image quality produced by the fading phenomena characteristic of radio indicates the practical restriction of radio television to fields where the much more reliable wire facilities are not available.

The Production and Utilization of Television Signals[1]

By FRANK GRAY, J. W. HORTON and R. C. MATHES

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Synopsis: The design of a television system, once the fundamental principles are understood, involves a detailed consideration of the methods by which the several important functions are to be performed.

(1) In the present system the initial signal wave is obtained by sweeping a spot of light over the subject in parallel lines completely scanning it once every 18th of a second. The light reflected is collected by large photoelectric cells which control the transmitted current. At the receiving station the picture current controls the brightness of a neon lamp from which the received image is built up by means of a small aperture moving in synchronism with the spot of light at the transmitting station. For presentation to a large audience television images may be produced by a neon lamp in the form of a grid having a large number of separate electrodes. A high frequency excitation controlled by the picture current is distributed to the successive electrodes in synchronism with the spot of light at the transmitting station.

(2) Space and time variations in the reflecting power of the subject are translated into time variations in signal strength. For design purposes these time variations are represented by component frequencies, a minimum band of which must be properly transmitted to insure an adequate reproduction of the image. Within this band there must be maintained a certain degree of uniformity in the efficiency of transmission of the separate components. Also, their phases must not be permitted to shift unduly in relation to each other.

(3) The design of the terminal amplifiers is based on the quantitatively determined characteristics of the photoelectric cells and of the neon lamps as well as on the limits imposed by the transmission study and by the characteristics of available transmission media, whether telephone line or radio system. The circuits employed at the transmitting station furnish an amplification such that the power delivered to the transmission medium is 10^{15} times the power received from the photoelectric cells.

Section I. Apparatus for the Analysis and Synthesis of the Image

THE introductory paper to this series of articles on television explained principles along which any television system must operate to transmit an image over a single pair of wires or other channel of communication. As the first step in such a transmission, the space variations in brightness from point to point in the view must be translated into time variations in an electrical current that can be sent over the channel of communication. This translation may be accomplished by a scanning process that operates on the view to produce the same effect as if the view were cut up into a single long strip and passed rapidly in front of a light-sensitive cell to generate an electrical current varying with the brightness along the strip. To eliminate flicker in the reconstructed image and also to follow moving

[1] Presented at the Summer Convention of the A. I. E. E., Detroit, Mich., June 20–24, 1927.

subjects in a view, the scanning process must be repeated and a new picture transmitted at least every sixteenth of a second.

Many purely theoretical methods could be, and have been, devised to accomplish such a scanning process and to translate a view into electrical currents or signals. Unfortunately, however, a practical system of television must operate with materials and conditions as they exist, and these practical limitations constitute the serious problems of television.

The high speeds and relatively large amplitudes with which any television scanning mechanism must move, and the necessity for synchronizing the transmitting and receiving apparatus lead to the use of synchronously rotating machines as apparently the only practical solution of the scanning and receiving problems. Consequently, the

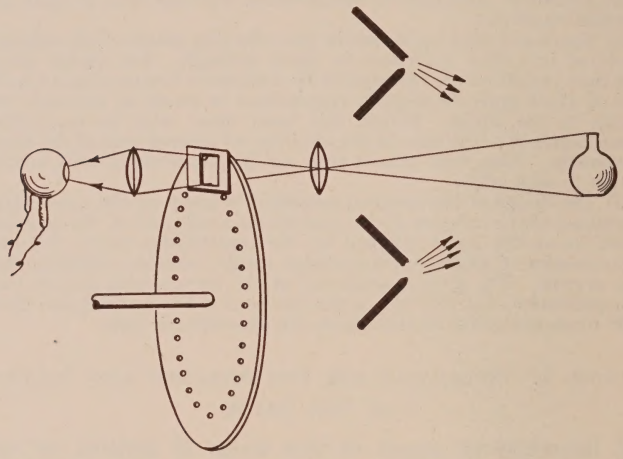


Fig. 1—Several light sources illuminate the subject; a lens forms an image which is scanned by a spiral of apertures, through which the light falls on a single photo-electric cell.

present television system has been designed to operate with continuously rotating mechanical parts.

The efficiency that must be secured in the optical part of any scanning method is fixed by the three following factors—the amount of picture detail that is to be transmitted, the efficiency of the light-sensitive cell, and the practical limit to amplifier systems. The first of these factors decides the area from which light can be collected at any one instant. In the present case this was fixed in an initial survey of the entire television problem when it was decided to confine the first attempt to the transmission of pictures as if they were made

up of 2500 small elemental areas; that is, to scan the view in a series of fifty parallel lines. The second factor is determined by the sensitivity of the potassium hydride photoelectric cell. This cell is, at the present time, the most efficient light-sensitive cell that can follow the rapid variations in light intensity without a time lag. The third factor, the limitation of amplifier systems, results from the extraneous currents that are present in metallic conductors and

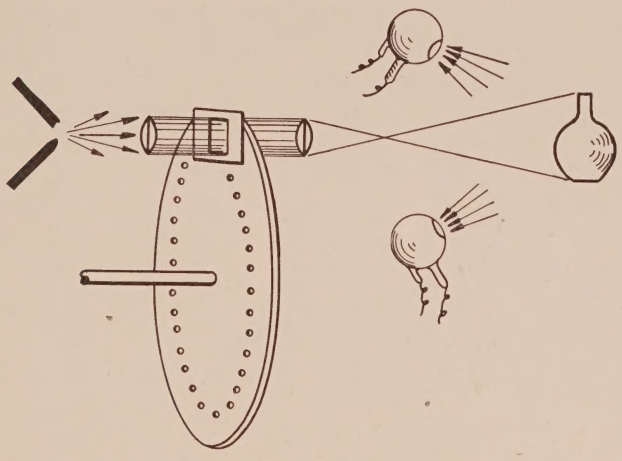


Fig. 2—Light from a single source is projected as a small moving spot on the subject; the reflected light is received by several photoelectric cells

amplifier tubes. The thermal agitation of the electrons in any input resistance generates such currents; and rapid variations in the number of electrons emitted from the hot filament of an amplifier tube also generate disturbing voltages. For successful amplification, the initial photoelectric current must be considerably larger than these extraneous currents. Consequently, the optical arrangement must be such that at any one instant it collects enough light from an elemental area of the view to generate this minimum permissible output current from the photoelectric cell.

The operation and advantages of the scanning method actually used in the present process for transmitting television images may be better understood by first considering a simple and analogous method illustrated by Fig. 1. The subject is illuminated by lights placed in front of it as shown. A lens forms an image of the subject on the rotating disk. This disk is pierced with a series of small holes or apertures arranged in the form of a spiral; and, as the disk rotates,

the apertures trace across the image one after the other in a series of parallel lines. The frame limits the size of the image and prevents more than one aperture being in the image at one time. Light, passing through an aperture as it travels across the image, falls in the light-sensitive cell and generates a picture current proportional to the brightness of the image from point to point along strips taken one after the other across the image.

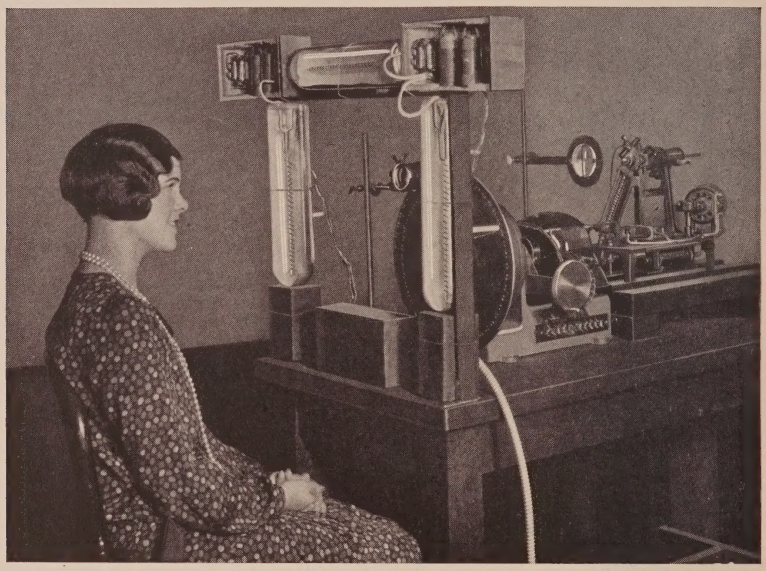


Fig. 3—Illustrative transmitting apparatus. Light from the arc lamp is condensed on the disk, which is driven by a high frequency synchronous motor. The disk carries a spiral of pin hole apertures, each of which in turn projects a moving spot of light on the subject. Reflected light is collected by three large photoelectric cells.

In any system such as that outlined above, which depends upon scanning an image of the view as formed by a lens, the efficiency of the system is ultimately limited, for any given size of image that can be scanned, by the ratio of aperture to focal length of the best lens that can be secured. Experiments show that, with the best lens available to form a one-inch-square image, it would be necessary to illuminate a subject with a 16,000-candle power arc at a distance of about four feet in order to secure an image bright enough for a photoelectric cell to give an output current above the noise level in an amplifier system. In other words, television would apparently be extremely inconvenient to the subject if it were to be carried out from an image formed by a lens.

In the system actually used for television transmission, this apparent limitation has been evaded by reversing the entire optical system of Fig. 1 and arranging it as shown diagrammatically in Fig. 2. Instead of scanning an image of the subject, the actual subject is scanned directly by a rapidly moving spot of light. An illustrative laboratory set-up, Fig. 3, shows the arrangement of parts in such a transmitting station. A fifteen-inch disk rotating approximately eighteen times per second carries a series of fifty small apertures arranged in the form of a spiral. A beam of light is condensed by a lens from a 40-ampere Sperry arc to intensely illuminate a limited area in the path of the moving apertures; and a slender, intense beam of light passes through each aperture as it moves across the illuminated area. A frame in front of the disk permits light to emerge from only one aperture at a time and the lens in front of the disk focuses an image of this moving aperture on the subject. As a result of this arrangement the subject is completely scanned in a series of successive, parallel lines by a rapidly moving spot of light, once for each revolution of the disk; and on account of the transient nature of the illumination the subject is scarcely aware that he is being exposed to it.

As the spot of light traces across the subject, light is diffusely reflected or scattered from the subject in all directions, and some of the light that is reflected forward passes into three large photoelectric cells placed just in front of the person who is being viewed. The current outputs from the three photoelectric cells operate in parallel into a common amplifier system. As the beam of light passes, for instance, across a person's eyebrow less light is reflected to the photoelectric cells, and as the beam passes across his forehead more light is reflected. Since the current output from the photoelectric cells is proportional to the received light, the current follows accurately the brightness of the various elemental areas of the subject's features as he is traced over by the scanning beam. This fluctuating current is unidirectional.

The actual operation of such an optical system, its influence on the lighting effects and quality of the reproduced image, may best be understood by noting that optically the system is identically the same as if all of the rays of light were reversed in direction to give an optical system equivalent to Fig. 1. The television apparatus sees the subject exactly as if rays of light came out of the photoelectric cells to illuminate the subject; the lens formed an image of the subject on the disk; and the apparatus scanned this image and reproduced it at the receiving end. The lights and shadows seen in the image are the same as if the subject were illuminated by three large lights in

the positions of the photoelectric cells and looked at from the position of the lens. It also follows from the above considerations that, within its range of resolving power, this scanning method will not only reproduce a plane subject, such as a drawing, but that it will also faithfully reproduce three-dimensional figures with sharp edges and elevations and depressions, just as well as they could be reproduced in a photograph.

In addition, because the light passes in an approximately parallel beam through a disk aperture, the slender beams of light sweeping across the region in front of the transmitter just barely overlap each other even at a considerable distance from the apparatus. Consequently, it is not necessary that the subject be at the exact positions at which the small apertures are sharply focussed; and within wide limits no confusion results as the subject moves toward or away from the apparatus. The brightness as well as the size of the received image decreases as the subject moves away from the photoelectric cells; and for good transmission of the human features, which reflect very little blue light to which the photoelectric cells are sensitive, a person should not be more than a few feet away from the cells.

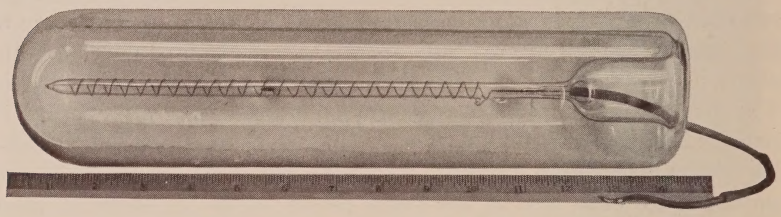


Fig. 4—Large photoelectric cell. The cell presents forty square inches of photosensitive surface to receive light reflected from a subject

This method of scanning permits two very large gains to be made in the amount of light available for producing photoelectric currents. The transient nature of the light permits a very intense illumination to be used without inconvenience to the subject. Furthermore, the optical efficiency of the system is not limited by the apertures of available lenses; but can be increased by using large photoelectric cells and more than one cell connected in parallel.

The photoelectric cells of the potassium hydride, gas-filled type used in the transmitting stations, were specially constructed for the purpose and are probably the largest photoelectric cells that have ever been made, Fig. 4. Three of these cells present an aperture of 120 square inches to collect the reflected light.

With this large collecting area and the strong light intensity that can be used for the transient illumination, the cells give an electrical output that, though still extremely small, is safely above the noise level of an amplifier system.

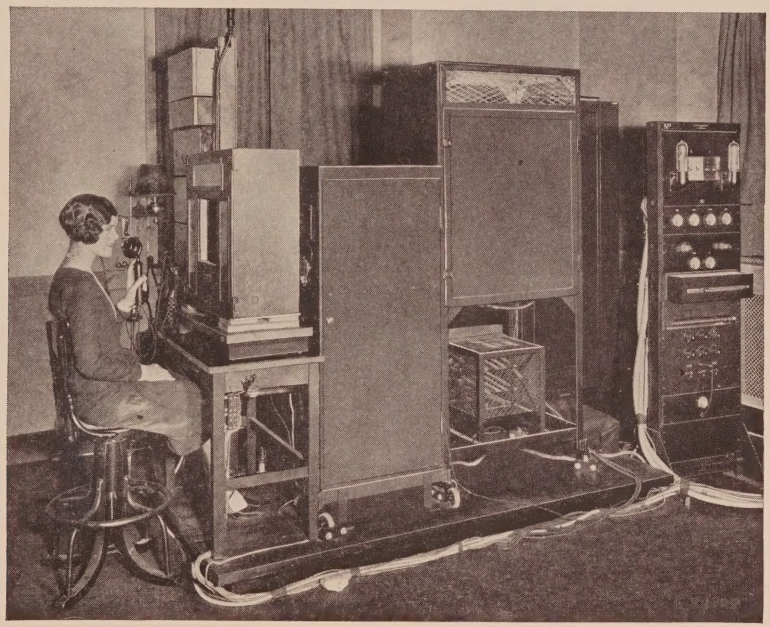


Fig. 5—Television transmitting apparatus. Sweeping beams of light pass out through the tunnel-like opening in the photoelectric cell case; light reflected from the subject is collected by three large photoelectric cells behind the screened openings.

A photograph, Fig. 5, shows the details of a television transmitting station as it is operated in the field. The arc, rotating disk and photoelectric cells are contained in separate cabinets and aligned as shown in the photographs. The three photoelectric cells and first stages of amplification are mounted in a shielded, sound-proof case. The slender, sweeping beam of light coming from the disk cabinet passes through the tunnel-like opening in the photoelectric cell case and scans the subject seated in front of it. The apparatus sees the person from light reflected back into the three large cells located just behind the screened openings in the case.

The variations of the feeble picture currents delivered from these photoelectric cells are highly amplified and transmitted over a wire or radio channel of communication by circuits described elsewhere in

this series of articles. At the receiving station this current shape is re-amplified, impressed on a direct current, and finally produces an image in the receiving apparatus.

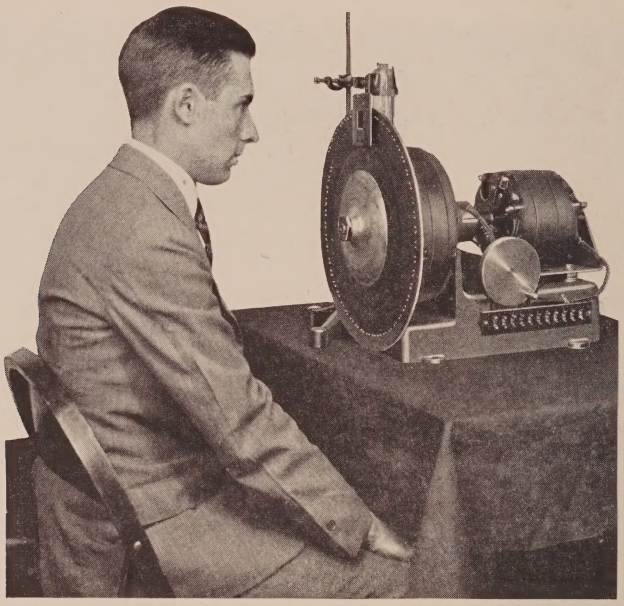


Fig. 6—Illustrative receiving apparatus. A neon lamp operated from the picture current illuminates a series of small apertures as they pass across the field of view; the observer sees an image reproduced in the frame.

A photograph, Fig. 6, shows an illustrative arrangement of the parts in one type of television receiver. An essential part of this type of receiver is a disk similar to the one at the transmitting station and also provided with fifty small apertures arranged in the form of a spiral. The driving motor rotates the disk in exact synchronism with the one at the transmitting station. The observer looks at a small rectangular opening or frame in front of the disk. This frame is of such dimensions that only one aperture can appear in the field of view at a time. As the disk rotates, the apertures pass across the frame one after the other in a series of parallel lines, each displaced a little from the preceding one until in one revolution of the disk the entire field has been covered. Beyond the disk is a special form of neon glow lamp shown in detail by Fig. 7. In this lamp, the cathode is a flat metal plate of a shape and area sufficient to entirely fill the field defined by the frame in front of the disk. The anode of the

glow lamp is a similar metal plate separated from the cathode by only a very small space (about one millimeter). At the proper gas pressure this space between the plates is within the "cathode dark space" where no discharge can pass. As a consequence, the glow discharge develops on the outer surface of the cathode, where it shows as a perfectly uniform, thin, brightly glowing layer.

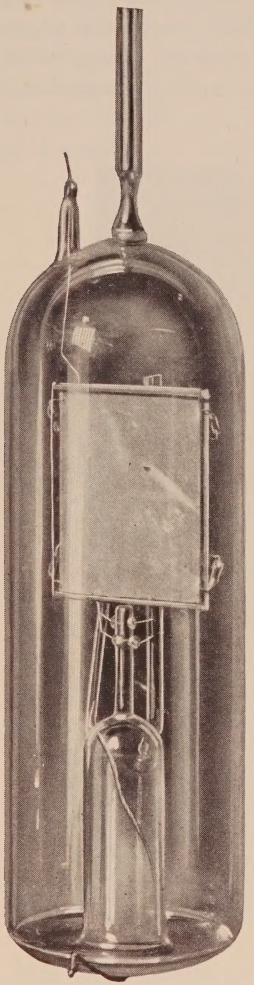


Fig. 7—Neon receiving lamp. The rectangular cathode is covered by a uniform layer of glow slightly larger than the field of view on a television disk

As an aperture in the disk moves across the field, the observer, looking through at the neon lamp behind the disk, sees the aperture as a bright point. When the disk is rotating at high speed, the observer, owing to the persistency of vision, sees a uniformly illuminated area in the frame, provided that a constant current is flowing through the lamp. (The line structure that would otherwise appear in the field is largely eliminated by using apertures that slightly overlap in their paths across the field.)

The brightness of the neon lamp is directly proportional to the current flowing through it; and when a picture is being received, the lamp is operated directly from the received picture current. As a result of the system just described, there is at any instant, in the field of view at the receiving station, a small aperture illuminated proportionally to the brightness of a corresponding spot on the distant subject. Consequently, the observer sees an image of the distant subject reproduced in the frame at the receiving station.

Fig. 8 shows the external appearance of the disk type of receiver in which the images appear. The disk rotates inside of a rectangular cabinet and the observer views the image through the shielding window. The largest disk, three feet in diameter, gives a 2 in. by 2½ in. rectangular image. Each television receiver is also equipped with a telephone receiver and transmitter; and it is possible for the observer to both see and converse with a distant person at the same time.

Considering the limited number of picture elements, a surprising amount of detail can be transmitted with this television system. A distant person can be seen and easily recognized and his motions can be plainly followed as he talks into a transmitter, turns the pages of a magazine and goes through other similar motions. Large-sized pictures in a magazine can be seen as the subject turns the pages and looks at them himself.

Fig. 8—Disk receiving apparatus. The observer looks through the shielding window at a picture on the 36-inch disk

An auxiliary television receiving system also accompanies each transmitting set and enables the operator to see that he is sending a satisfactory picture current out over the channel of communication. This auxiliary or pilot picture is formed on the scanning disk itself. A small fraction of the outgoing picture current is tapped off and amplified to operate a neon lamp, which is placed behind the disk ninety degrees around from the scanning beam. An image of the subject may thus be seen on the scanning disk just as at a receiving

station. To correct for the ninety-degree phase shift, the spiral of apertures on the transmitting disk is continued by additional apertures a quarter of a turn beyond the starting point. The first turn alone of the spiral is used for scanning; and the last turn alone, to form the pilot image; consequently, this image appears exactly in frame. A small mirror on the front of the motor cabinet reflects this image to the operator and enables him to see the character of the picture that he is sending out over the channel of communication.

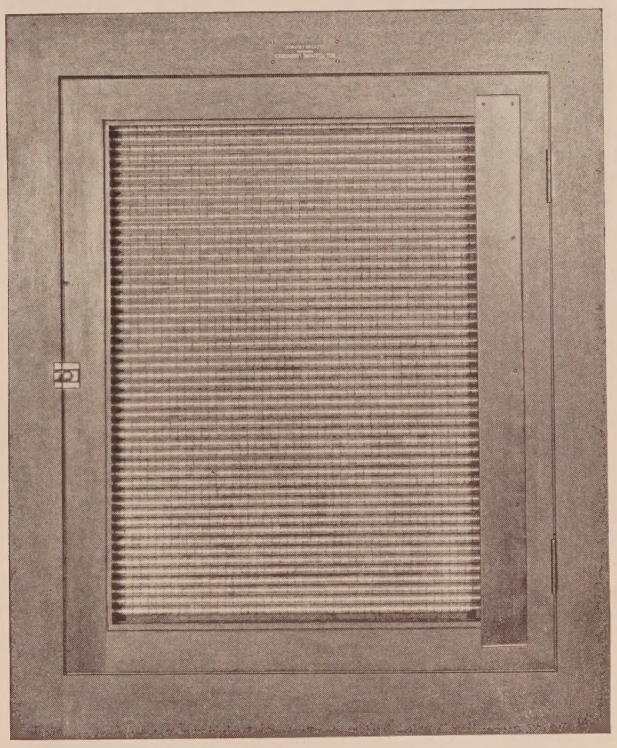


Fig. 9—Large grid. The large grid is a neon lamp with 2500 electrodes on a tube bent back and forth to form a luminous screen that is visible throughout a large auditorium.

When it is desirable to present television images to a large audience, a special grid type of receiver is used. The grid has the appearance of an illuminated screen and can be seen throughout a large auditorium. The image is not projected on the screen from a lantern like a moving picture; such optical projection would be inefficient and demand

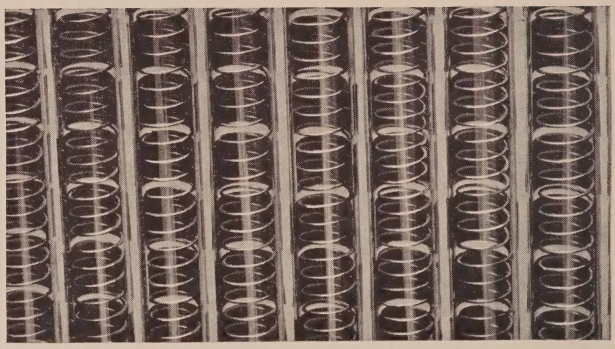


Fig. 10—Detailed structure of the grid. The exterior electrodes are pieces of metal foil cemented to the outside of the tube. The interior electrode is a long spiral of wire.

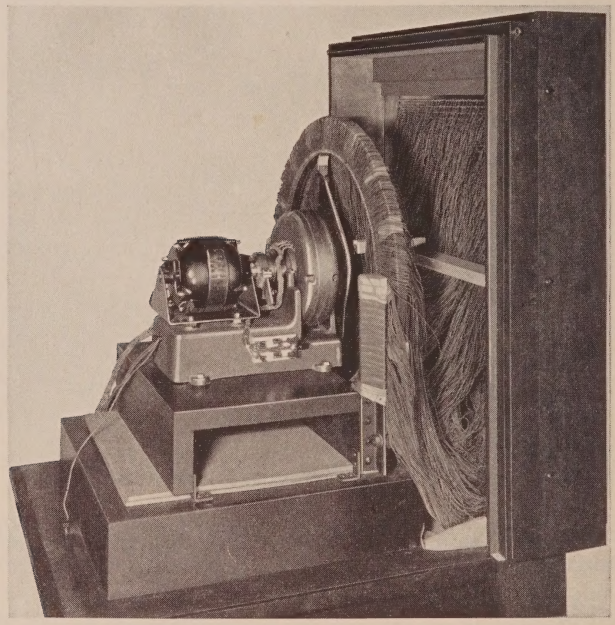


Fig. 11—Distributor and wiring. High frequency current is distributed by 2500 wires to successive electrodes of the grid from 2500 bars on a high speed distributor.

the electrical control of an impractical amount of light. The picture current itself is distributed by a commutator to successive elemental areas of a large neon lamp. This lamp, as shown in Fig. 9, consists of a single, long, neon-filled tube bent back and forth to give a series of fifty parallel sections of tubing. The tube has one interior electrode and 2500 exterior electrodes cemented along the back side of the glass tubing, Fig. 10. A high frequency voltage applied to the

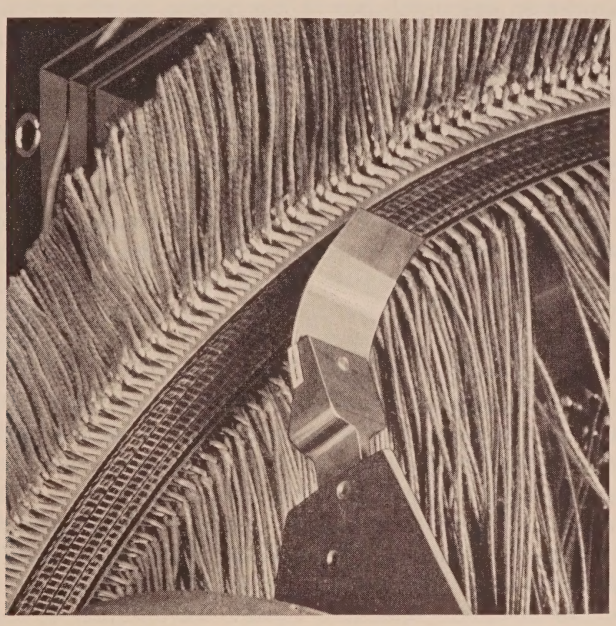


Fig. 12—Details of the distributor. The bars are arranged in four rows each displaced with respect to the other three. The sliding brush is a strip of thin sheet metal.

interior electrode and any one of the exterior electrodes will cause the tube to glow in front of that particular electrode. The glow discharge actually passes to the inside wall of the glass tubing and the high frequency current flows by a capacity effect out through the glass wall to the exterior electrode. The high frequency voltage is commutated to the electrodes in succession from 2500 bars on a distributor, Fig. 11, with a brush, Fig. 12, rotating synchronously with the disk at a transmitting station. Consequently, a spot of light moves rapidly and repeatedly across the grid in a series of parallel lines one after the other and in synchronism with the scanning beam at the transmitting station. With a constant exciting voltage the

grid appears as a uniformly illuminated screen; but, when the high frequency voltage is modulated by the received picture current, an image of the distant subject is produced on the screen and his motions can be followed just as in the smaller images formed on a disk.

This method of presenting television images to a large audience permits a very efficient use of the available energy to reproduce a picture. The modulated current produces a glow discharge that exactly covers an elemental area of the picture on the screen and is viewed directly by the audience; consequently, there is absolutely no loss of energy after the picture current has been converted into light. In addition, each illuminated area of the screen responds to the picture current in the same manner; the exterior electrodes are exactly alike, and the use of a single tube assures the same pressure and purity of neon throughout the grid.

Fig. 9 shows such a screen set up for demonstration in an auditorium. A loud speaker is mounted just below the screen and it is thus possible for a large audience to both see and listen to a distant person at the same time.

Section II. The Television Signal Wave

So far it has been assumed that the electrical signal wave is perfectly transmitted between the conversion devices which transform the light variations into electrical variations and back again. Perfect transmission is, however, impossible with practical apparatus. There are certain requirements placed upon the generated signal wave by the characteristics of practical communication channels, and reciprocally certain demands are made upon a transmission system by the inherent nature of an adequate television signal. In addition to exploring these mutual requirements experimentally it is desirable to analyze them in such a way that, as far as possible, quantitative expression may be given to them. This expression in the case of the signal wave is best made by the methods of the Fourier analysis; considering the signal as made up of many sine wave components of various frequencies. The requirement on the signal may then be described in terms of these components and the requirements on the connecting transmission system in terms of attenuation and phase characteristics over a band of frequencies. These requirements will now be discussed as a basis for the subject matter of the succeeding section of this paper and of the following companion papers of this group on "Wire Transmission Systems for Television" and "Radio Transmission Systems for Television."

The problems to be discussed may be conveniently considered under three headings:

(*a*) The Character of the Television Signal.

(*b*) Requirements upon the Signal Wave Set by the Characteristics of Available Transmission Channels.

(*c*) Requirements which the Transmission Channels must meet in order to carry Television Signals.

(*a*) *The Character of the Television Signal.* As we have seen, the voltage produced across a resistance in series with the photoelectric cell is a fluctuating unidirectional potential. The generated signal therefore has frequency components beginning at and including zero frequency. The value of the voltage at any instant is roughly proportional to the average reflected illumination at that instant from an illuminated spot whose size depends upon the apertures in the scanning disk. At any point where there is a sudden change in the tone value of the subject there will also be a sharp change in the generated voltage. It will, therefore, be seen that but for the limits of speed of action of the photoelectric cell and its connected circuits the generated signals would tend to include components over the whole frequency range up to infinity. Since it is possible to effectively transmit but a limited range of these components, the width and location of the frequency band necessary for the acceptable reproduction of a given size and structure of image must be determined. It is convenient to consider first the low frequency end of the band.

In the early experimental work it was soon found that in attempting to amplify the lower frequencies by the use of direct current amplifiers, unstable conditions of operation were reached before sufficient amplification was obtained to operate the receiving apparatus. Experiments were then made with resistance-condenser coupled amplifiers which showed that, if the efficiency of such an amplifier at the frequency equal to the number of pictures sent per second was not more than about two T U below its average efficiency for the transmitted range, acceptable reproduction of the picture was secured together with stable operation of the amplifiers. When the low frequency cut-off of the amplifier was set much above this, spurious shadows were introduced into the picture. That there will be a critical lower frequency for the transmission of an unchanging scene is obvious since the Fourier series into which the signal may be analyzed starts with a constant term and the sine wave terms begin with the picture frequency and include a vast number of its harmonics. If the constant component (d-c.) is removed, the lowest frequency which remains to be transmitted is therefore the picture frequency.

The effect of removing the d-c. component of the signal can be qualitatively traced in a simple manner. Imagine three types of still

pictures or scenes to be transmitted by the system. Let the first be quite dark in general effect and require fluctuations in the signal current of a certain average amount for its transmission. Such a picture would have a low direct current component. Let the second picture consist largely of medium grays and require about the same fluctuations in signal intensity for its delineation. Such a picture will have a medium direct current component. Let the third picture be very light in general effect with such difference in light and shadow as would require the same fluctuations in signal intensity as the other two pictures. Such a picture would have a relatively high direct current component. In passing through a resistance-condenser coupled amplifier, the signals for all three types of pictures would be changed from fluctuations superimposed upon direct current to alternating currents, all of about the same average value.

At the receiving end of the circuit the direct current component may be reinserted by superimposing the alternating current fluctuations upon a fixed value of direct current such as the steady state current in the last amplifier tube. This direct current component would give the best average results if it corresponded to that suitable for the gray picture, which would, of course, then be most nearly correctly reproduced. However, most of the detail of the dark and light scenes would also be reproduced though the tone values would be distributed about a medium gray. Fortunately a change in character of this kind has proven for the most part unimportant. Where it is important it can be taken care of very simply by providing, at the receiving end, means, either manual or automatic, for changing, in accordance with the type of scene being transmitted, the magnitude of the unidirectional current upon which the received alternating current is superposed, which amounts simply to the restoration of the direct current.

In the case of scenes which are changing, however, frequencies lower than picture frequency will in general be generated and their suppression may be expected to affect to some degree the perfection of the picture. In effect, these frequencies are analogous to changes in tone values in the case of still pictures and their elimination results in fluctuations in the apparent brightness of the image. This effect is not disturbing with many types of subjects, as for example in the reproduction of the face.

One remarkable result of not transmitting the direct current component of the signal in the case of the reflected beam method of scanning is that the television transmitting apparatus can be located and operated in a well-lighted room, for if this general illumination is

constant it simply increases the direct current component of the signal. Similarly if the scene itself contains a source of steady light, this will be visible only in so far as it reflects the scanning beam.

Turning now to the upper part of the frequency range, experimental data on the highest necessary components were obtained by the use of circuits with low pass instead of high pass characteristics. With the television terminal apparatus operating at 17.7 pictures per second, it was found that a filter whose phase distortion had been corrected over practically all of its pass band of 15,000 cycles produced a degradation in image quality which was just detectable when the human countenance was being transmitted. Since the electrical terminal apparatus without the filters would efficiently transmit frequencies higher than this, the experiment showed either that frequencies higher than this were not present in the generated signal, that they were not effectively reproduced, or that they contribute little to the appearance of the image. This upper limit to the useful frequency range for this apparatus is rather lower than was anticipated from the initial survey, but because of psychological factors (decreased discrimination of tone values for fine details, apparent improved resolution when the subject is moving, etc.) it proves satisfactory for television purposes.

It is of importance, however, to know where the limitation in frequency range occurs in the apparatus and how it might be modified. Considerable information on this point is obtained by studying the nature of the distortion introduced by the aperture in the optical system and that introduced by frequency limitation in the electrical part of the system. It is convenient to consider them together as the type of distortion turns out to be similar for the two cases. This distortion may be considered most simply in relation to the type of signal corresponding to a sudden unit change in tone value at some point in the subject. With an ideal television system in which the instantaneous values of signal current are at all times proportional to the tone values of the points being scanned, the resulting signal would be represented by the graph of Fig. 13. Such a consideration involves no real loss in generality as any signal shape may be considered as the result of infinitesimal abrupt changes in intensity.

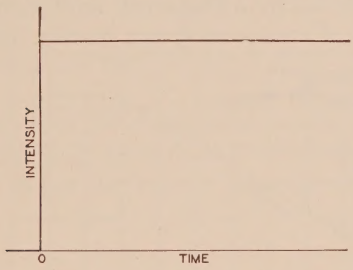


Fig. 13—Elementary signal change

It is readily seen that if a square aperture passes with uniform velocity over a part of the picture having an abrupt change from dark to light the result is that we get a signal from the photoelectric cell which, instead of building up instantaneously, builds up linearly during a time, T, Fig. 14, which is the time required for the aperture to pass a given point.[1] The net effect is an apparent sluggishness in the response of the system. The dotted curve of Fig. 14 shows the integrated illumination passing through a circular aperture of a diameter corresponding to the same time, T, for the condition of Fig. 13. Due to the simpler analysis the discussion will be carried out in terms of the square aperture though the sluggishness due to the round one is seen to be slightly less.

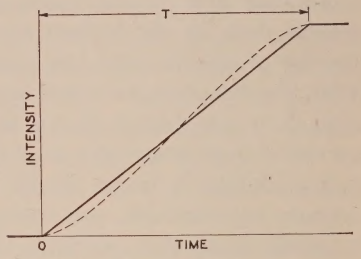


Fig. 14—Elementary signal change as distorted by a square aperture

Now this kind of sluggishness in response is quite similar to that introduced in the electrical part of the system when the upper frequencies are cut out or not transmitted as efficiently as the lower ones. The effect of frequency limitation can be investigated theoretically in a fairly simple fashion if we make the ideal assumption that all frequencies are transmitted without distortion up to a cut-off frequency, f_c, and extinguished beyond it. In Appendix I, it is shown how the signal of Fig. 14 is affected by a frequency limitation of this type. We can then plot a set of curves as shown on Fig. 15

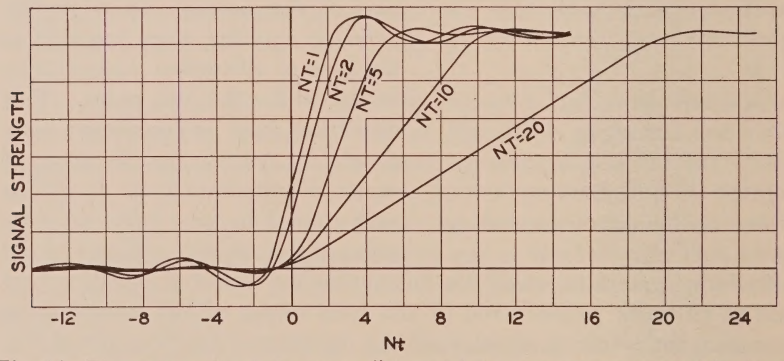


Fig. 15—Elementary signal change as distorted by a square aperture and by ideal frequency restriction

[1] This effect of aperture distortion was pointed out in the paper "Transmission of Pictures over Telephone Lines" by Ives, Horton, Parker and Clark, *B. S.* T. J., April, 1925.

from which we can measure the total time of rise due to both the aperture and frequency limitation. The abscissa is the product of $N = 2\pi f_c$ and the time, t. Any one curve serves for a wide range of values of N and T as long as their product is the same. Call the new time of rise τ. Then we can plot a relation as on Fig. 16 between

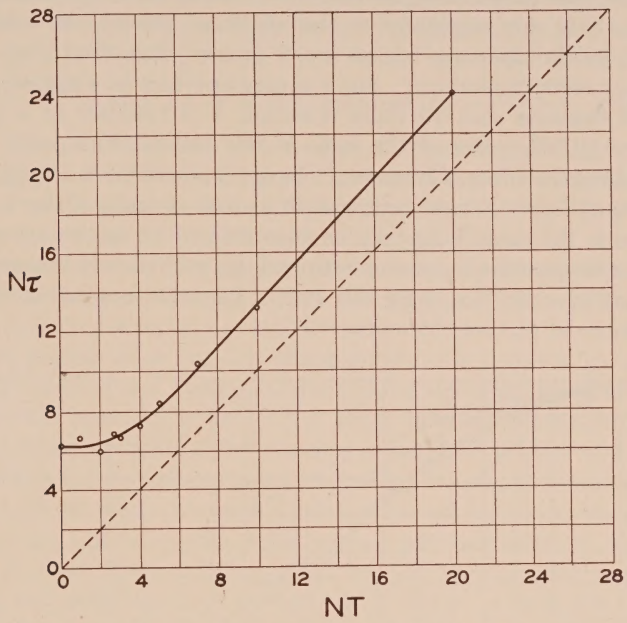


Fig. 16—Sluggishness due to distortion as a function of the aperture width and frequency restriction

$N\tau$ and NT from which we can draw conclusions as to the relative effects of aperture and frequency distortion.

Below the knee of this curve we have approximately

$$N\tau = 2\pi$$

$$\tau = \frac{1}{f_c}$$

and the frequency cut-off determines the whole distortion. Similarly above the knee

$$N\tau = NT + \pi$$

$$\tau = T + \frac{1}{2f_c}$$

and the controlling influence is that of the aperture.

Unless one effect is much more easily remedied than the other, the knee of the curve appears a reasonable point to select for operation. At the knee $NT_k = 2\pi f_c T_k = \pi$ and $T_k = 1/2f_c$. At this point the total lag is not much greater than that due to the frequency restriction alone and is $1/f_c$ or twice T_k. That is, at this point, the additional lag in the time of rise of signal due to the restricted frequency range is equal to that due originally to the aperture, though the additional lag due to the aperture is not much greater than that due to the frequency restriction alone. For a square aperture in a square picture of 2500 elements sent 16 times a second $T = 1/40{,}000$ of a second, and $f_c = 20{,}000$ cycles at the knee of the curve. The point on the curve where the effect of frequency restriction introduces a sluggishness in following light changes comparable to that introduced by a square aperture is the same frequency as that arrived at as the upper limit to useful frequencies by considerations from still picture transmission, in the introductory paper by Mr. Ives. Its value is equal to one half the number of picture elements.

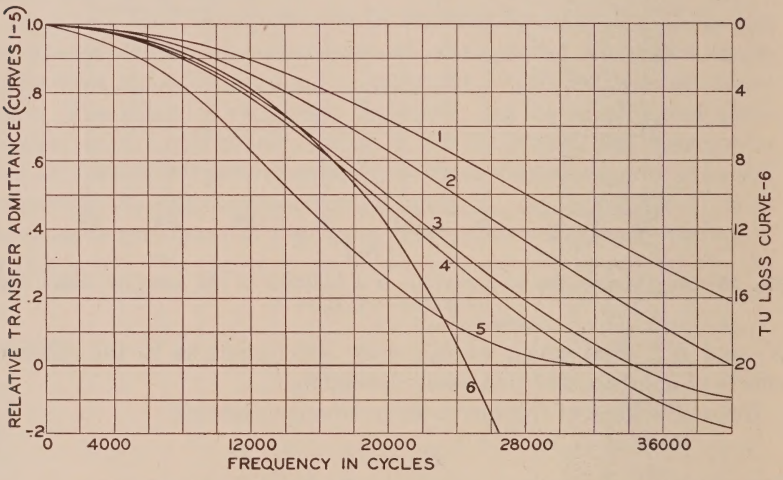


Fig. 17—Equivalent transfer admittance of various apertures

It has furthermore been found possible to determine ideal electrical transmission characteristics or equivalent transfer admittances of circuits which produce exactly the same distortions as various types of apertures. While it appears impossible at present to construct a physical circuit which will produce such characteristics over the whole frequency range, the problem is not difficult if we limit ourselves to the most important frequency band. This is of interest as it points out

the possibility of compensating for the effect of the aperture by putting in an electrical network with frequency transmission characteristics the inverse of those so determined. Within the range of important frequencies it turns out that the effect of the aperture is the same as that of a network which changes merely the relative amplitudes of the frequencies into which the picture signal may be analyzed. Neglecting constant multiplying factors, the relative variation over the frequency range for a square aperture is given by the factor $\frac{\sin T\omega/2}{\omega}$ and for a round aperture by $\frac{J_1(T\omega/2)}{\omega}$, where, as before, T is the maximum time for the aperture to pass a given point and J_1 is the Bessel's function of the first order. The derivation of these factors is given in Appendix II. On Fig. 17, Curve 1 gives the relative values of the equivalent transfer admittance for the square aperture and Curve 2 for an inscribed circular aperture, both in case of a 50-line scanned picture which is square and sent 16 times per second. T then is equal to 1/40,000 sec.

In the system as set up for demonstration the image is rectangular with the vertical and horizontal dimensions in about the ratio 5 to 4. The circular aperture is about 1¼ times 1/50 of the vertical height and the scanning is done 17.7 times a second. T is then 3.53×10^{-5} seconds and Curve 3 gives the corresponding frequency characteristics. Curve 4 shows that a square aperture of the same area as the circular aperture for Curve 3 gives a fairly good approximation to Curve 3. Curve 5 gives the combined effect of the two circular apertures, sending and receiving, corresponding to Curve 3. Curve 6 is Curve 5 plotted in terms of T U on the right hand scale.

An inspection of this last curve indicates that this frequency attenuation characteristic of the aperture introduces a considerable loss at 15,000 cycles and leaves little of the signal components above 20,000 cycles. To see if an electrical circuit of characteristics inverse to those of the aperture would materially improve the resolution of the image, the circuit,[1] which, together with its frequency characteristics, is shown in Fig. 18, was inserted between the sending and receiving amplifiers. It was designed to compensate for most of the aperture distortion and its phase distortion was made small below 20,000 cycles. On the fan-shaped test pattern of Fig. 19 a noticeable improvement was observed, the black and white angles being resolved closer to the tip of the pattern. In the case of faces the improvement appeared to be very little but could be detected

[1] This is a constant resistance type of corrective network or equalizer. See Chap. XVIII, "Transmission Circuits for Telephonic Communication," K. S. Johnson.

in the slightly better definition of sharp narrow lines such as the frames of horn-rimmed spectacles. When a system of considerable attenuation is employed between the sending and receiving terminals, it would in general be preferable to split the equalizing between the sending and receiving ends to make the best use of the sending end power in riding over interference.

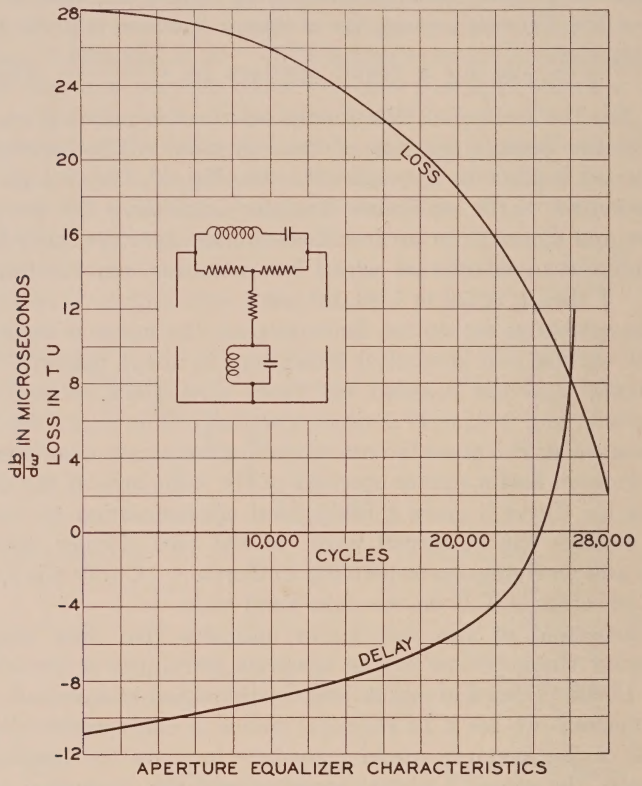


Fig. 18—Circuit for equalizing the aperture effect and its amplitude and phase characteristics

In arriving at the amount of electrical equalization which shall be adopted in any particular case it must of course be borne in mind that as the aperture is made narrower the amount of distortion introduced by it becomes less. As we narrow the aperture, however, the available illumination becomes less and the signal generated by the photoelectric cell becomes smaller. A limit is therefore soon reached at which the difficulties of amplification become greater than the

difficulties of equalization and a minimum practical aperture width is thereby determined. If the distortion is corrected by narrowing the aperture, it is apparent that the apparatus will generate, at but little lower than the correct relative efficiency, frequencies much higher than those thought necessary from the more general considerations in Mr. Ives' introductory paper. Decision as to the desirable frequency transmission band for the connecting communication channel would be no different for either method of reducing the distortion due to the aperture.

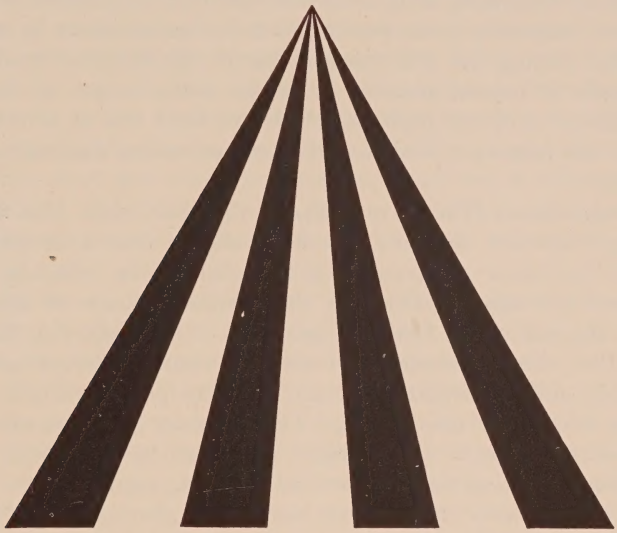


Fig. 19

In summary, then, we may say that experiment and theory show that the lowest frequency essential to satisfactory results is the picture frequency, and the highest frequency required is approximately one half the number of picture elements scanned per second.

(*b*) *Requirements upon the Signal Wave Set by the Characteristics of Available Transmission Channels.* The limitations upon the signal wave set by present available communication channels are:

1. The magnitude of the signal necessary to override the interference to which such channels are subject.

2. The frequency range which such channels can transmit.

The first of these is self-explanatory. It determines the required amplification and load capacity of the transmitting apparatus. In the companion paper on *Wire Transmission Systems for Television* are

the data on interference and on permissible signal to noise ratio which were used in the design of the terminal transmitting amplifiers to be described in the latter part of this paper.

In considering the frequency range of lines, it was apparent in the beginning that the wire channel might include sections of cable. With existing loading systems for such cables a frequency range of not over 40,000 cycles appeared available. The terminal apparatus was therefore designed to deliver a generated signal whose essential components lay well within this limit, and the laboratory tests mentioned in the preceding section showed that this requirement was met.

A lower frequency limit was imposed by the necessity of a transformer for joining the transmission line to the terminal equipment. Fortunately it proved possible to design transformers as described in the final part of this paper in which this limit was at or below the essential low frequency limit found in the preceding discussion of the signal wave.

(*c*) *Requirements Which Transmission Channels Must Meet in Order to Carry Television Signals.* We have shown that a certain band width of frequency components is essential to the adequate reproduction of the image. This sets the frequency limits of the transmission channel which must be provided. It is essential, however, that within these transmission limits the channel should present a reasonably uniform attenuation, and that the phase relations should be fairly accurately maintained. The problem as presented to the transmission engineers of wire, radio and terminal equipment for the recent demonstration was to meet the following requirements:

First, transmission must be provided for frequencies between about 10 cycles and 20,000 cycles.

Second, the amplitude frequency characteristics within this range should be uniform to about $\pm$ 2 T U.

Third, the phase shift through the range should be maintained so that the slope of its characteristic as a function of frequency is constant to $\pm$ 10 or 20 micro-seconds over all but the lowest part of the frequency range. There, about 50 times this limit was considered the maximum permissible.

These requirements were arrived at by considerations based on theory and experiments on television and analogy to similar requirements in telephotography. The first requirement follows directly from the discussion of the essential frequencies in the signal. The following paragraphs are intended to illustrate the significance of the remaining requirements.

As we have as yet no quantitative measure of the goodness of

reproduction of the image, the matter of the second and third transmission requirements on received amplitude and phase characteristics over the frequency scale is one which had to be decided largely on the basis of the experimental results and judgment based on general considerations. We have already seen that the removal of the very lowest frequencies simply changes the tone value of the whole picture. It may be similarly reasoned that departures from the average efficiency of transmission in the lower part of the frequency range would result in the appearance of diffuse shadows or high lights. Likewise, it may be concluded that broad deviations from the average efficiency of transmission in the uppermost part of the signal frequency range would result in the accentuation or the fading out of the finer detail of the scene. Steep slopes in the amplitude-frequency curve would result in the superposition of oscillations upon signals representing sudden changes in intensity. To reduce these effects every reasonable effort was made to keep the variations in the amplitude characteristic with frequency as slight as possible, aiming to hold these characteristics for the separate parts of the demonstration system to within $\pm$ 2 T U or better.

In addition to transmitting the component frequencies with the same relative efficiency as regards amplitude, it is also particularly essential in television to send them through the system with small relative phase shifts; that is, with constant velocity or what is equivalent, a phase shift proportional to frequency. It has long been known in optical theory that the envelope of a group of waves of nearly the same wave-length and nearly the same frequency may travel along with a "group velocity" somewhat different from the phase velocities of the component elements. If the system has but small departures from a flat amplitude-frequency characteristic and from a linear phase shift frequency characteristic, it can be shown that the time of group transmission or "envelope delay" is given by $db/d\omega^2$, the slope of the curve obtained by plotting the phase shift, b, for the system, against the angular velocity, $\omega = 2\pi f$. The time of transmission of a crest for any sine wave component of frequency $\omega/2\pi$ is, of course, given by b/ω. If $b = c\omega$, $b/\omega = c$ and $db/d\omega = c$. Then the phase and envelope times of transmission are equal and all frequencies as well as their group envelopes get over in the same time. If b is given in radians, $db/d\omega$ is given in seconds. In general a knowledge of b as a function of ω is necessary and sufficient to determine the phase distortion. A knowledge of $db/d\omega$ as a function of ω is not sufficient to determine all factors in signal distortion. It is, however, often easier to measure with the needed accuracy and in transmission

systems such as have been used for still pictures and television has proven a useful index of phase characteristics.

After a preliminary estimate from experience with still pictures that the limit on $db/d\omega$ should be $\pm$ 10 microseconds, an electrical network consisting of five sections of a simple lattice structure was used for testing the effect of phase distortion with television apparatus. This network introduced negligible amplitude distortion and a drift in the value of $db/d\omega$ of 50 microseconds over the frequency range of 0 to 20,000 cycles. Its effect was perceptible in blurring the image of a face and it decidedly affected a sharp pattern of two parallel lines of such width and spacing as to be just within the resolving power of the apparatus. This variation of $db/d\omega$ was about $2\frac{1}{2}$ times greater than that postulated. Hence $\pm$ 10 microseconds was agreed on as a desirable limit for $db/d\omega$, though it was felt that this limit might be exceeded by a factor of two in restricted parts of the frequency band.

When this network was combined with a filter the slope of whose envelope delay curve was in the opposite direction so that over the greater part of the frequency range the combined delay of the two

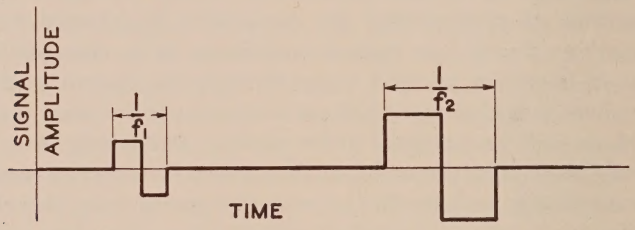


Fig. 20—Signal details of concentrated frequency spectrum for illustrating the effect of envelope delay

circuits was constant and equal to 140 microseconds, this time delay effect was very graphically brought out. Every time the combined circuit was cut in, the undistorted received image jumped to a new position a little over 10 per cent of the width of the picture to one side in the direction of scanning.

To see why $db/d\omega$ should be maintained at a constant value, consider two sharply defined details near together in the picture which would produce a variation in signal intensity with time as indicated in Fig. 20. Imagine each to be cyclically continued so that the small detail defines a frequency f_1 and the other defines a frequency f_2. It is then known from Fourier analysis that the frequency spectra of the two details are chiefly concentrated around the frequencies f_1 and f_2. If $db/d\omega$ is appreciably different at the frequencies f_1 and f_2 for any part of the

system, the two details will be displaced relatively to each other along the line of scanning and, in most cases, if this shift is appreciable, some change in the shape of the signal wave defining each detail results with further increase in the distortion. The same relative shift would occur if the narrow detail were located upon the broader one, in which case such a shift would be more apparent. It would seem reasonable to expect then that differences in the envelope time of transmission comparable to a whole picture element (about 28 microseconds in the demonstration apparatus) would be noticeable.

In most images very few details will have signal shapes, as in this special case, in which the frequency components are concentrated in narrow frequency bands. An abrupt change in signal strength, for instance, is represented by components distributed over the whole frequency range. We can imagine these frequencies divided into any arbitrary number of groups, each of which determines a wave form. When these wave forms are added together, they will reproduce the original abrupt change in signal strength. If, however, they are sent through a system in which the envelope delays for the different groups are unequal, the individual wave forms will be relatively displaced and will no longer combine correctly. As a result the image is blurred. For some types of phase distortion the effect appears as an oscillatory transient following sudden changes in intensity.

It was furthermore found by experiment that the limit of ± 10 microseconds was not necessary for the lower frequencies. Reference to the delay characteristics of the transformers described in the latter part of this paper shows that in the lower part of the frequency scale deviations from the nearly uniform value of delay at the upper frequencies appear of magnitude greater than 100 microseconds. When the signal was sent through these transformers, however, there was no observable distortion of the image. The requirements are therefore much more lenient at the low frequencies.

In the terminal apparatus the problem of meeting the above outlined phase transmission requirements was not a very serious one. The circuits involved are such that when a flat amplitude-frequency characteristic had been secured the phase distortion was also negligible.

Section III. Terminal Circuits for Sending and Receiving Television Signals

The preceding sections have discussed the methods by which an object, the image of which is to be transmitted, is made to control the time variations in a light, thus giving a luminous signal wave, and the means by which the image may be reconstructed with the aid of an

electric signal wave corresponding to this initial luminous wave in its relative instantaneous amplitudes. Certain important relations between the characteristics of the signal wave and the resulting image have been pointed out. There remains the question of obtaining an electric signal wave suitable for long distance transmission and of providing for the control of the illumination at the receiving terminal by the electric signal wave as delivered by the transmission medium.

In the use of wire lines for television it is fortunately true that a suitably prepared open-wire circuit possesses a frequency range sufficient for the transmission of all the essential components of the signal wave. Details regarding the characteristics of the wire circuits are given in a companion paper by Messrs. Gannett and Green, from whose work are obtained data essential to the design of the terminal equipment. These data fix the power level at which the signal should be delivered to the line and the power level which will be available at the receiving end. When the transmission is by radio it is, of course, necessary to effect a frequency translation in order to secure a wave suitable for radiation and transmission through the ether. In this case, however, the radio system, which is described in a paper by Mr. E. L. Nelson, when considered as a whole may be conveniently taken as a system capable of the transmission of a signal wave occupying the same frequency range as that supplied to the wire circuits. In fact the design of the radio system is such that it may be used interchangeably with the wire line in so far as the remaining electrical terminal equipment is concerned.

The terminal circuits, then, fall into two groups: first, those used at the transmitting terminal for building up the wave controlled by the time variations in light to the power level required by the line; and second, those used at the receiving terminal to bring the wave delivered by the line to the proper form for controlling the luminous sources from which the received picture is built up.

Transmitting Circuits

Starting with the photoelectric cell in which the initial luminous signal wave is converted to an electric signal wave, we are interested in the magnitude of various pertinent constants. The cell may be considered for our purposes as an impedance, the value of which is determined by the quantity of light reaching it. With no illumination at all this impedance is almost entirely a capacitance of the order of 10 m.m.f. When the cell is illuminated this capacitance becomes effectively shunted by a very small conductance which is roughly proportional to the square of the voltage between the electrodes.

For a fixed potential the magnitude of this conductance is nearly a linear function of the illumination. With a suitable potential in series with the cell, then, there is obtained a current the amplitude of which is proportional to the quantity of light reaching the cell.

In order to connect the photoelectric cell to the amplifier, there is introduced in series with the cell and its polarizing battery a pure resistance the voltage drop across which is used to control the grid potential of the first tube. It is desirable, of course, to make this resistance high in order to have available as much voltage as possible. Its value is, however, limited by two considerations. The added series conductance must not be so low that it appreciably disturbs the linear relation between the illumination and the total conductance of the circuit. The voltage drop must also be so small, in comparison with the total potential in the circuit, that the photoelectric cell operates at an approximately constant polarizing potential.

In view of the extremely small voltage of the electric signal wave as delivered by the photoelectric cell circuit, it is essential that great care be taken to prevent such interference as may enter the initial amplifier stages from approaching a comparable magnitude. The most troublesome sources of interference are electrostatic induction, electromagnetic induction, mechanical vibration, and acoustic vibration. By mechanical vibration is meant disturbances transmitted through the supports as the result of building vibrations and similar phenomena. By acoustic vibrations are meant impulses transmitted through the air which strike the several elements of the amplifier and cause motion which results in variations in their electrical constants. Electrical disturbances are reduced to a minimum by placing the amplifier as close as possible to the photoelectric cells, thereby keeping the leads short, which avoids electrostatic pick-up and also prevents the formation of closed loops of any appreciable size, thus avoiding electromagnetic induction. The amplifier is provided with a very complete electrical shield and both the shielded amplifier and the photoelectric cells are placed in a carefully shielded cabinet.

The tubes used, namely, the so-called "peanut" tubes, are, under ordinary conditions, remarkably free from any microphonic action. At the very low signal levels used, however, certain extra precautions have to be taken against this effect. In addition to lining the amplifier box with sound-absorbing material, the tubes themselves have been wrapped in felt and placed within a heavy lead case. This prevents such acoustic disturbances as reach the interior of the amplifier container from having any noticeable effect on the tube. The lead container is supported entirely by an elastic suspension and thus

serves a dual function, as the heavy mass, supported in this way, is capable of little response to such mechanical vibrations as may be transmitted through the cabinet and the walls of the amplifier shield. With these precautions it has been found possible to make the effect of all external disturbances of about the magnitude of the thermal disturbances referred to in the first part of the paper.

A schematic diagram of the amplifier tubes directly associated with the photoelectric cell is given in Fig. 21. Attention has already been

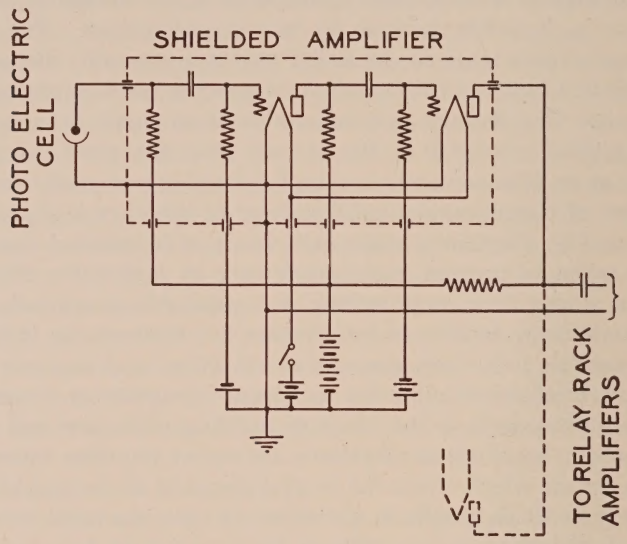


Fig. 21—Schematic of vacuum tube amplifier used with photoelectric cells

called to the fact that the initial signal, that is, the time variation of the light reflected from the scanned object, contains a direct current component. The amplification of this direct current component is, as has been stated, out of the question in any amplifier intended for continued operation over long periods of time. The requirements as to the range of frequencies to be transmitted, as discussed in the preceding section, make it necessary to provide a circuit having practically uniform efficiency from 10 cycles to above 20 kilocycles. The relative phase shift of the several components must also be kept very small. In view of the large amplification and consequent large number of stages necessary, it has been thought impracticable to use transformer coupling between all stages as the aggregate frequency and phase distortion might well be greater than could be tolerated. The so-called resistance capacitance coupling has therefore been used.

The arrangement of the several photoelectric cells in their cabinet, as shown in Fig. 3, is such that one amplifier can be connected directly to two of the cells leaving the third to operate a second amplifier. The outputs of these two amplifiers are then connected in parallel to the common battery supply equipment shown at the bottom of the two vertical cells.

By the use of two stages of amplification in the photoelectric cell amplifier, the signal is brought to such a level that it may be carried by suitably shielded leads to other amplifiers outside the photoelectric cell cabinet. This permits of using the convenient relay rack form of mounting. The signal level is, however, still low and may be adequately handled in amplifier units which differ but little from those used with the photoelectric cell.

The remaining requirements placed on the amplifiers at the transmitting terminal are those set by the telephone line. One of primary importance is that which determines the amount of energy needed. In order that the signal wave shall be of such magnitude that any interference present in the line may be negligible in comparison, it is desired that the alternating current delivered by the final amplifier stage shall be at least 4 milliamperes into an impedance of 600 ohms. The energy to be supplied is, therefore, approximately 0.01 watt, which determines the choice of the last amplifier stage. To build up the signal to a value sufficient to operate this output tube it has been found that eight stages of the small-sized tubes and one stage of greater load-carrying capacity must be used. The total amplification given by these ten stages is approximately 130 T U. It is through this known gain of the amplifiers that we get our only accurate quantitative data as to the magnitude of the initial signal wave. This comes out to be about 10^{-15} watts or, with a 100,000-ohm resistance in series with the photoelectric cell, the potential available at the first tube is roughly 10 microvolts.

The characteristics of the line also determine the means by which it shall be coupled to the final amplifier stage. In order to secure the proper impedance matching and to prevent the line from being unbalanced with respect to ground, it was felt desirable to use transformers if possible rather than to attempt the design of a tube circuit capable of meeting the requirements directly. The problem included both output and input transformers, and specified an amplitude-frequency characteristic constant to within $\pm$ 0.5 T U from 10 cycles to 25,000 cycles. The input coils intended for use at the receiving terminal had the additional requirement that a minimum of interference current should be induced in the secondary due to potentials

between the line and ground. The success with which this problem has been solved is shown by the curves of Fig. 22. Curve 1 is the

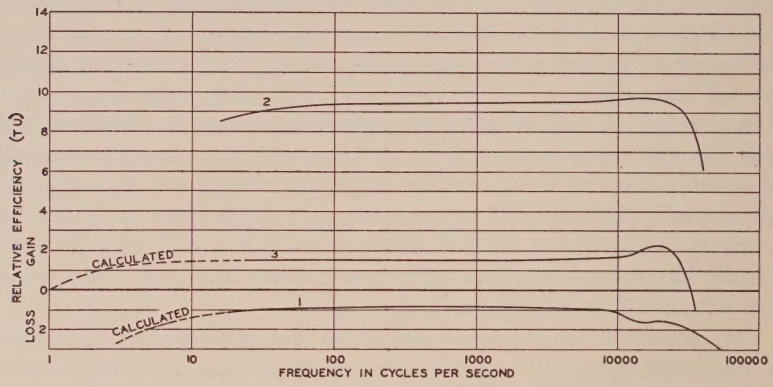


Fig. 22—Transmission characteristics of iron core transformers

1. Output transformer connected between impedances of 2000 ohms and 600 ohms.
2. Input transformer having voltage step-up of 6.5 connected between 600-ohm line and vacuum tube.
3. Input transformer having voltage step-up of 2.5 connected between 600-ohm line and vacuum tube.

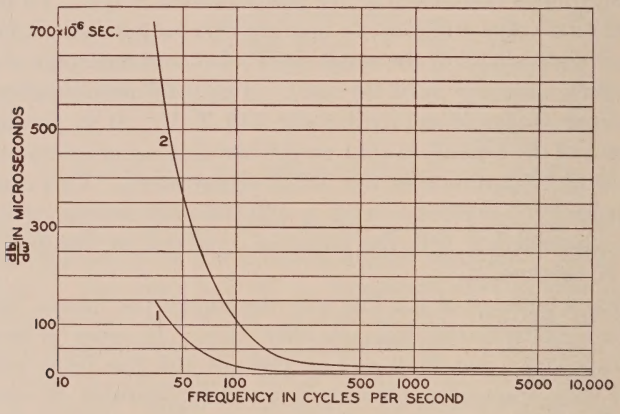


Fig. 23—Envelope delay characteristics of transformers

1. Output transformer
2. High ratio input transformer

transmission characteristic of the output transformer which is designed to work between impedances of 2000 ohms and 600 ohms when connected between generator and load circuits having these values.

Curves 2 and 3 show the effective transmission gain of transformers having voltage step-ups of 6.5 and 2.5 respectively, when used to connect the first stage of the vacuum tube amplifier to a 600-ohm generator impedance. The envelope delay curves for the output transformer and for the high ratio input transformer are given in Fig. 23. Photographs of the coils are given in Fig. 24. A large

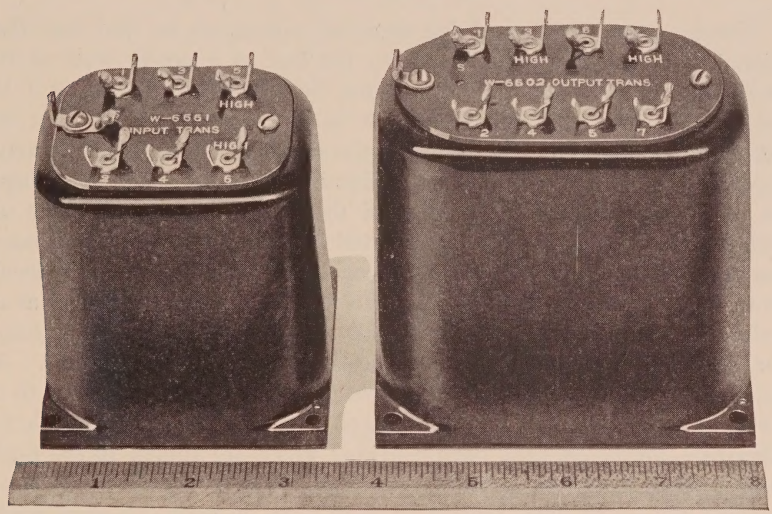


Fig. 24—Transformers used for coupling amplifier circuits to long distance telephone lines

factor in being able to get coils of this type lay in the availability of permalloy for the core material. The output transformer is connected to the amplifier through a blocking condenser in order to avoid possible saturation in the core due to the passage of direct current.

Measurements made on the several elements of the amplifier system have shown that its overall frequency characteristic is constant to within $\pm$ 2 T U from 10 to 20,000 cycles.

In an amplifier having as much gain as that just described it is apparent that a slight change in the potential of the power supply will cause a considerable change in the overall efficiency. Moreover, variations in the intensity of the light source used with the scanning system will cause corresponding changes in the intensity of the initial luminous signal wave. To insure that the energy level supplied to the line is at all times of the proper magnitude a level indicator has been provided to permit continuous observations of the output of the amplifier. This consists of an amplifier-rectifier circuit so arranged

that the space current of the last tube is a function of the alternating current voltage impressed on the first, being roughly proportional to the square of its amplitude. By means of a direct current milliammeter, therefore, it is possible to keep a very accurate check on the amplitude of the signal delivered to the line.

Receiving Circuit

Coming now to the receiving terminal equipment we find that the signal wave which was delivered to the line at a power level of 10 milliwatts may, under some conditions, be reduced to a level 50 T U below this, or to 0.1 microwatt. It is, therefore, necessary first of all to provide amplification to bring the signal to a level where it may operate the circuits controlling the illumination from which the image is to be reconstructed. In view of the fact that several types of receiving equipment are to be operated and also since the signal may be derived from any of several sources, either wire line, radio or local transmitting station, it is desirable to fix some one energy level as a reference point and to bring all signals to this value so that they may be supplied interchangeably to the several receiving systems. A convenient reference level is that already set as the proper input to a telephone line, namely, 10 milliwatts. At the receiving terminal, therefore, amplifiers have been provided which are similar to the final stages used at the transmitting terminal. These include units containing the small-sized tubes and terminate in units identical with that supplying current to the line except that the output transformer is omitted. The first stage is, as mentioned in the preceding section, connected to the line through an input transformer. The amplifiers associated with the several incoming signals are each provided with a level indicator of the type already described. These terminal amplifiers and the several receiving circuits are all terminated in jacks, exactly like telephone circuits, and it is possible, therefore, to connect any receiving machine to any desired transmitting station simply by patching the proper jacks together, exactly as telephone circuits are connected at the central office.

Before describing the final stages of the amplifier circuits it is necessary first to examine the properties of the light source which is to be controlled. In the case of the disk receiving machines described in the first section of this paper it is recalled that a single neon lamp is used having a rectangular electrode the entire area of which glows at each instant with an intensity proportional to the intensity of the initial luminous signal. The current voltage characteristic of a typical neon lamp is given in Fig. 25. It will be seen that no current flows

until the voltage across the lamp reaches the breakdown potential which, in the example shown, is about 210 volts. From this point on the current increases linearly with respect to voltages in excess of a value somewhat below the breakdown point. It will also be seen

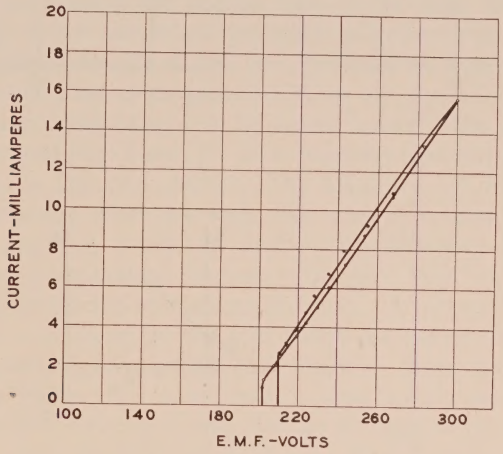
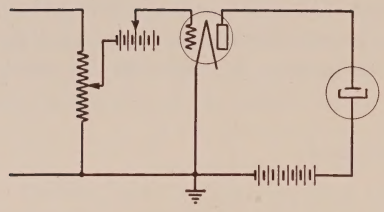


Fig. 25—Current voltage characteristic of typical neon lamp

from the curve that the value of current depends somewhat upon the direction in which the voltage is changing. In most cases, however, the function comes sufficiently close to being single valued for our present purposes. In view of the well-established linear correspondence between the intensity of the illumination resulting from the glow discharge and the current, it is required to so arrange the circuits that the current through the lamp is at all times proportional to the illumination at the transmitting terminal.

It will be recalled that the electric signal wave as transmitted through the various amplifier circuits differs fundamentally from the initial luminous wave in that the direct current component has been eliminated. It is necessary, therefore, to restore this component before the changes in light intensity at the receiving terminal will follow those at the transmitting terminal. The several factors entering at this point may perhaps best be examined in terms of an elementary circuit such as given in Fig. 26. In this case the neon lamp is connected in series with the plate circuit of a vacuum tube and its polarizing battery. The circuit may be considered for the present as equivalent to one in which the neon tube is replaced by an ohmic resistance and in which the potential of the polarizing battery is



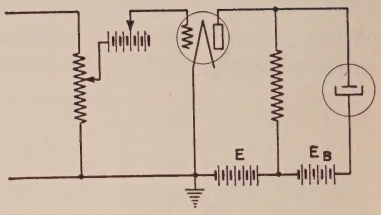


Fig. 26—Circuit schematic and operating characteristic of neon lamp amplifier

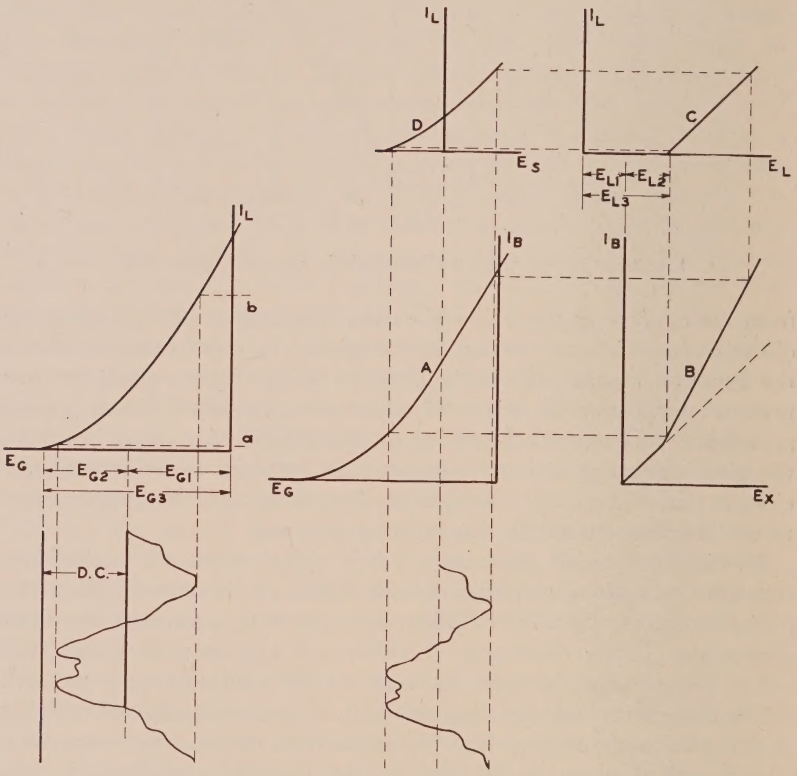


Fig. 27—Circuit schematic and operating characteristics of circuit arranged for linear operation of neon lamp

reduced by an amount corresponding to the back e.m.f. of the lamp. Under these conditions the relation between current—and therefore illumination—and the voltage on the grid of the vacuum tube is as shown by the curve given with the figure. This curve takes into account the change in potential between the plate and filament of the vacuum tube due to the voltage drop in the lamp resistance. If the reactances in the circuit are negligible, this curve may be taken as the dynamic characteristic of this portion of the system.

Let us assume that to properly build up the desired image at the receiving terminal the light is to be varied between the limits set by the two horizontal lines *a* and *b*. It is apparent that two adjustments are necessary in the grid circuit. The amplitude of the impressed alternating current must be such that the difference between its positive and negative maxima is equal to the difference between the grid voltages corresponding to these currents. This is taken care of by suitable adjustments of the amplification. It is further necessary that the bias introduced by the grid polarizing battery be such that the positive and negative peaks coincide with these same values of grid voltage. Under these conditions the grid battery must be looked upon as supplying two absolutely distinct biases, one the bias for the tube and the other the bias for the signal. For example, if the signal wave as delivered to the grid circuit contained the original d-c. component properly amplified, it would be necessary to adjust the system so that zero current would be obtained with no impressed signal. To accomplish this the tube would require the negative grid bias E_{G3}. Variations in signal voltage would then be considered as taking place about this value of grid potential as the origin. Thus E_{G3} is the operating bias of the tube. To properly locate the signal wave, however, it is necessary to add the positive bias E_{G2}. It will be seen from the curve that this bias corresponds exactly to the direct current component which is to be restored to the signal. The sum of these two biases, obviously, gives the actual bias, E_{G1}, with which the tube is operated.

In the circuit as shown the well-known curvature of the vacuum tube prevents us from obtaining a linear relation between the current through the neon lamp and the signal voltage. This condition may be overcome by a number of circuit modifications of which that shown in Fig. 27 is typical. Instead of connecting the neon lamp and the vacuum tube directly in series, a resistance is provided across which is set up a potential, E_X, proportional to the current through it. Across this resistance is shunted the neon lamp and a biasing battery, E_B. The adjustment of this circuit is indicated by the curves shown.

Curve A expresses the relation between the grid potential of the vacuum tube and its plate current. Curve B shows the relation between this same plate current and the voltage across the external resistance. When no current is flowing through the vacuum tube, the potential of the biasing battery is insufficient to break down the neon lamp and no current flows through the circuit containing the neon lamp and the plate circuit resistance. As the current through the vacuum tube is increased from zero, the total current flowing is that through the resistance branch. When, however, the potential drop across this resistance reaches such a magnitude that, together with the potential of the biasing battery, it is sufficient to break down the neon lamp, the latter will begin to draw current which thereafter increases linearly with further increases in the voltage, E_X, across the external resistance. The voltage across the neon lamp itself differs from that across the resistance by the amount of the battery E_B. The relation between the neon lamp current and the voltage across it, as given by Curve C, may therefore be plotted directly above the characteristic just discussed by displacing the vertical axis an amount corresponding to E_B. This amount is shown as E_{L1}. Here again we have two separate biases controlled by a single adjustment. The potential E_{L2} is fixed by the minimum plate current which can be taken from the tube without departing too seriously from the linear portion of the tube characteristic. It is, therefore, an operating bias of the circuit which is unaffected by any characteristic of the neon lamp. The latter, however, must be operated with a bias E_{L3} corresponding to its effective back e.m.f. As in the case of the grid circuit bias just considered, the bias E_{L1} actually introduced into the circuit is the difference between these two independently determined biases.

By projecting values of lamp current horizontally and plotting their intersections with vertical projections through the corresponding grid potentials on the vacuum tube characteristic we obtain Curve D, which expresses the relation between the instantaneous value of the signal and of the current in the neon lamp as derived from the characteristics of the several elements of the circuit. Inasmuch as the intensity of the illumination is proportional to the lamp current, it will be seen that we have approached the desired linear correspondence between the instantaneous values of the signal and of the light.

It will be noted that care has to be exercised to insure that the alternating current as impressed on the last vacuum tube is of the proper polarity. If it is not, the received image will be a negative instead of a positive. This may be controlled either by the connections to any one of the transformers or by the number of vacuum

tube stages. With an even number of stages the polarity will be reversed from that given by an odd number. This is because an increase in negative potential on the grid of a vacuum tube causes a decrease in the space current and hence a decrease in the negative potential applied to the grid of the next tube.

In the case of the grid type of lamp with the individual external electrodes, the impedance to which energy must be supplied differs materially from that presented by the rectangular electrode lamp already described. For low voltages the impedance between any electrode and the central helix is effectively a capacitance of the order of 6 m.m.f. When, however, the voltage gradient in the interior of the tube becomes sufficient to break down the gas and cause a discharge to take place, the capacitance is increased to about 15 m.m.f. In fact, the tube may be looked upon as consisting of two capacitances connected in series. When the applied potential is sufficient to break down the gas and cause a glow discharge, that capacitance corresponding to the portion of the path inside the tube is effectively shunted by an ohmic resistance. The minimum discharge potential has been found to be independent of frequency over a wide range, but the current between electrodes is inversely proportional to the frequency because of the presence of the capacitance between the electrode and the glowing gas. Now, the brightness of the discharge is a function of the current sustaining it so that it becomes desirable to use high frequencies in order to get sufficient light without going to prohibitively high potentials. It is also desirable to operate at such a portion of the frequency scale that the percentage difference between the limits of the range shall be small, thus avoiding signal distortion due to the effect referred to above. There is, however, a definite upper limit to the frequency beyond which it would be impossible to operate because of the stray capacitances in the cable connecting the grid to the distributor. It has been found feasible to operate at a frequency of the order of a half million cycles.

The circuit problem, therefore, involves the production of a high frequency wave which varies in amplitude in accordance with the amplitude of the received picture signal. The solution has been conveniently obtained by using a radio broadcast transmitter the voice frequency circuits of which have been so modified that the extended range of frequencies required might be handled with minimum distortion.

The envelope of the 500-kilocycle wave modulated by the picture signal, as shown in Fig. 28, is proportional to the signal amplitude plus a direct current biasing component of such magnitude that when the

envelope reaches 160 volts the tube fails to light. This corresponds to a black area in the picture. When no picture signal is being received, the amplitude of the unmodulated carrier wave causes the tube to light at average brightness, corresponding to the locally introduced d-c. component of the signal. It follows, then, that the amplitude of

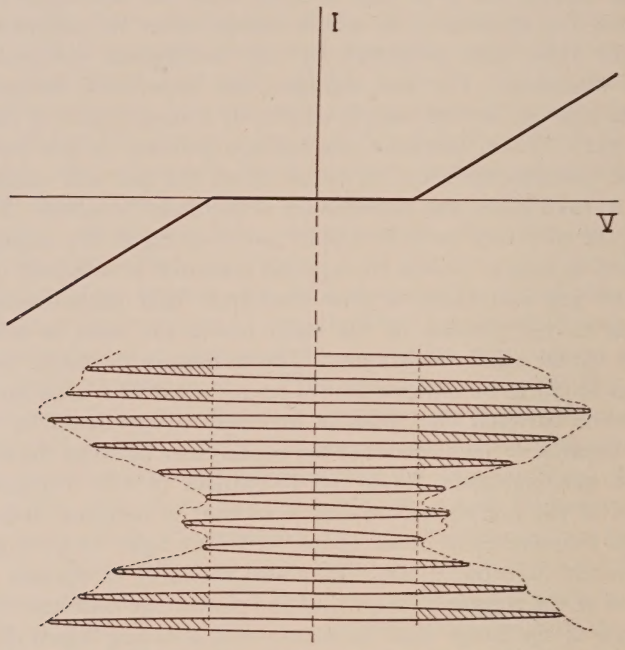


Fig. 28—Diagrammatic representation of relation between modulated high frequency wave impressed on grid type neon lamp and lamp characteristics. Intensity of glow is proportional to shaded area.

the unmodulated carrier is fixed, as in a previous example, by the joint requirements of two biases, that of the lamp and that of the signal bias.

There is a slight distortion inherent in this method due to the fact that the light, which is proportional to the shaded area of the curve of Fig. 28, is not strictly proportional to the amplitude of the envelope with respect to the 160-volt limit. This is, of course, because these peaks are portions of a sine wave and hence the time variation of the glow resulting from any given carrier cycle is a function of its amplitude. The effect is small, however, being most noticeable at low values of illumination.

In the case of the grid-lamp receiver the signal amplitude is adjusted,

as for the disk receiver, by a potentiometer in the low frequency portion of the circuit. The carrier amplitude, however, is adjusted by varying the plate potential applied to the oscillating tube. The coupling to the lamp is made by connecting the central helix and the distributor brush across a portion of the condenser of the oscillating circuit.

The frequency-amplitude relation of the envelope has been made practically constant by employing resistance capacitance coupling in the signal input amplifiers, by providing extremely high inductance retard coils for the modulator—which is of the Heising type—and by inserting resistance in the oscillating circuit to provide sufficient damping. The relations between the original picture signal and the envelope of the high frequency wave, with respect to both amplitude and phase shift, were observed over the signal frequency range by means of a Braun tube and found to be satisfactory. The impedance of the connecting leads to the commutator was also measured and found to have a negligible effect on the frequency and damping of the oscillating circuit.

It has been found that there may be a lag between the time when the potential is applied to an electrode and the time when the gas breaks down. This is especially true following an interval during which there has been no discharge within the tube. Because of this those electrodes which are the first to be connected in any one of the parallel portions of the tube may fail to light. To overcome this effect a small pilot electrode is kept glowing at the left-hand end of each tube, thus irradiating the branch in such a way that the illumination of all electrodes follows immediately upon the application of potential. These pilot electrodes, which are obscured from view of the audience by the frame of the grid, are supplied by means of an auxiliary connection to the oscillator with a potential somewhat lower than that ordinarily impressed upon the picture segments.

Appendix I

The signal of Fig. 13 in the body of the paper may be represented as follows:

$$\left.\begin{aligned} f(t) &= 0 && \text{for } t < 0 \\ &= \frac{t}{T} && \text{for } 0 < t < T \\ &= 1 && \text{for } t > T \end{aligned}\right\} \qquad (1)$$

or by a Fourier integral in the form

$$f(t) = \frac{1}{\pi}\int_0^\infty d\omega \int_{-\infty}^{\infty} f(\lambda)\cos\omega(t-\lambda)d\lambda, \qquad (2)$$

where λ is an auxiliary variable of integration and ω is 2π times the frequency. To get the effect of sending this signal through a system which transmits all frequencies without phase or amplitude distortion up to a cut-off frequency f_c it is only necessary to replace the upper limit of the first integral sign by N where $N = 2\pi f_c$. Thus:

$$F(t) = \frac{1}{\pi}\int_0^N d\omega \int_{-\infty}^{\infty} f(\lambda)\cos\omega(t-\lambda)d\lambda.$$

Then from (1):

$$F(t) = \frac{1}{\pi}\int_0^N d\omega \int_0^T \frac{\lambda}{T}\cos\omega(t-\lambda)d\lambda + \frac{1}{\pi}\int_0^N d\omega \int_T^\infty \cos\omega(t-\lambda)d\lambda$$

$$= \frac{1}{\pi NT}\Big\{\cos Nt - \cos N(t-T)$$

$$+ Nt[Si(Nt) - Si(Nt-NT)]\Big\} + \frac{1}{\pi}\Big[\pi + Si(Nt-NT)\Big].$$

If we write $Nt = x$, $NT = z$, and $\pi F(t) = y(x)$, then

$$y(x) = \frac{1}{z}\Big\{\cos x - \cos(x-z) + x[Si(x) - Si(x-z)]\Big\}$$

$$+ \frac{\pi}{2} + Si(x-z),$$

where

$$Si(x) = \int_0^x \frac{\sin x}{x}dx.$$

A series of graphs of $y(x)$ for different values of the product NT is given in Fig. 15 in the body of the paper. These are generalized curves, the time scale depending on the particular value of cut-off frequency used. From these curves we can get the additional lag in the time, τ, in the rise of these curves over the original time T in Fig. 14.

Appendix II

Let $f(t)$ be the instantaneous intensity of the picture, and let it be represented by a Fourier integral:

$$f(t) = \int_0^\infty A(\omega)\cos[t\omega + \Phi(\omega)]d\omega. \qquad (1)$$

Let T = time required for the aperture to pass a given point, Fig. 29.

Let $\varphi(t_1)$ be height of aperture at distance t_1 from its center.

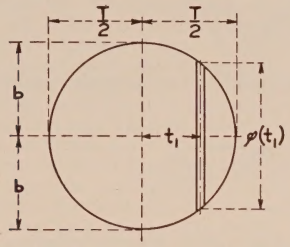


Fig. 29

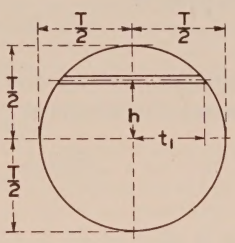


Fig. 30

Analysis of the aperture

The instantaneous amount of light passing through the aperture is

$$\begin{aligned} F(t) &= \int_{t-T/2}^{t+T/2} \varphi(t_1) f(t_1)\, dt_1 \\ &= \int_{t-T/2}^{t+T/2} \varphi(t_1)\, dt_1 \int_0^{\infty} A(\omega) \cos\left[t_1\omega + \Phi(\omega)\right] d\omega \qquad (2) \\ &= \int_0^{\infty} A(\omega)\, d\omega \int_{t-T/2}^{t+T/2} \varphi(t_1) \cos\left[t_1\omega + \Phi(\omega)\right] dt_1. \end{aligned}$$

In the case of the rectangular aperture

$$\varphi(t_1) = \text{a constant} \qquad (3)$$

and, except for a negligible constant factor,

$$\begin{aligned} F(t) &= \int_0^{\infty} A(\omega)\, d\omega \int_{t-T/2}^{t+T/2} \cos\left[t_1\omega + \Phi(\omega)\right] dt_1 \\ &= \int_0^{\infty} A(\omega) \left\{ \frac{\sin\left[(t + T/2)\omega + \Phi(\omega)\right]}{\omega} \right. \\ &\qquad \left. - \frac{\sin\left[(t - T/2)\omega + \Phi(\omega)\right]}{\omega} \right\} d\omega \qquad (4) \\ &= 2 \int_0^{\infty} A(\omega) \frac{\sin T\omega/2}{\omega} \cos\left[t\omega + \Phi(\omega)\right] d\omega. \end{aligned}$$

The transformation from $f(t)$ to $F(t)$ amounts merely to changing the relative amplitude of the Fourier components of $f(t)$ by a factor proportional to $\dfrac{\sin T\omega/2}{\omega}$.

In the case of the circular aperture we can divide the aperture up into narrow elements parallel to the direction of motion, as shown in Fig. 30. Elements at a distance h from the middle line of the strip have lengths

$$2t_1 = 2\sqrt{T^2/4 - h^2}. \tag{5}$$

Each element considered as an independent *rectangular* aperture has the frequency characteristic

$$\frac{\sin t_1\omega}{\omega} = \frac{\sin \omega\sqrt{T^2/4 - h^2}}{\omega}.$$

The mean of all of these elementary frequency characteristics is

$$\begin{aligned}\frac{1}{T}\int_{-T/2}^{T/2}\frac{1}{\omega}\sin\left[\omega\sqrt{T^2/4 - h^2}\right]dh &= \frac{2}{T\omega}\int_0^{T/2}\sin\left[\omega\sqrt{T^2/4 - h^2}\right]dh \\ &= \frac{1}{\omega}\int_0^{T/2}\sin\left[\omega T/2\sqrt{1 - \frac{4h^2}{T^2}}\right]\frac{2dh}{T} \qquad (6) \\ &= \frac{1}{\omega}\int_0^1 \sin\left[T\omega/2\sqrt{1 - x^2}\right]dx \\ &= \frac{\pi}{2\omega}J_1(T\omega/2),\end{aligned}$$

where J_1 indicates a Bessel function of the first order. In place of the amplitude variation function $\frac{\sin(T\omega/2)}{\omega}$ for the square aperture, we have $\frac{J_1(T\omega/2)}{\omega}$ as such a factor. From the very nature of the physical processes under consideration it follows that this average value of the elementary frequency characteristics is effectively the frequency characteristic of the aperture as a whole.

Synchronization of Television [1]

By H. M. STOLLER and E. R. MORTON

Bell Telephone Laboratories, Incorporated

Synopsis: Synchronization of Television is the problem of holding two scanning disks so that their phase displacement is always less than four and one third minutes of arc. A 240-pole synchronous motor of the variable reluctance type is used as a basis. Coupled to it a direct current motor carries the steady component of the load. Hunting is eliminated by a condenser in series with the two synchronous motors whose capacitance is slightly less than that required to tune the circuit.

As the motor might lock into step in any of 120 possible angular positions, only one of which would give the proper phase relations, a two-pole motor, with only one locking position, was provided by tapping the armature of the direct current motor at two points and bringing out the leads to slip rings. This was used for synchronizing while the 240-pole motor, connected subsequently, held the close synchronism required. The disks rotate at 1062.5 r.p.m. which gives 17.7 cycles on the two-pole and 2125 cycles on the 240-pole motor.

For transmission the synchronizing current is attenuated to a level of .6 milliwatt and amplified at the receiving end. The 17.7-cycle current is an undesirably low frequency for transmission over telephone cables and so is used to modulate a 760-cycle current through a polarized relay. This is demodulated at the receiving end, where a polarized relay by interrupting a local battery current gives a rectangular wave which acts through vacuum tubes on the field of the direct-current motor.

THE problem of synchronization involved in television transmitting and receiving equipment is similar in principle to any synchronous motor problem but the requirements are of such a special nature that it is necessary to employ unusual features of motor design and control circuits to secure the required results.

General Requirements

At the transmitting end a scanning disk is employed containing 50 holes spirally spaced around the periphery of the disk rotating at a speed of 1060 r.p.m.[2] It is desired to rotate a similar scanning disk at the receiving end so that the hole through which the observer is looking at a neon lamp will be in a position corresponding to the hole which is transmitting light at the same instant at the transmitting end. Since there are 50 holes in each disk, the holes will be spaced apart 7.2 degrees, thus 7.2 degrees of arc correspond at the receiving end to the width of the picture. Since the horizontal resolving power is approximately the same as the vertical (0.02 of the picture dimension), the arc occupied by a picture element is 0.02×7.2 or 0.144 degree. In order not to appreciably impair the quality of the picture,

[1] Presented at the Summer Convention of the A. I. E. E., Detroit, Mich., June 20–24, 1927.

[2] This speed was determined by transmission considerations and is discussed in the companion paper by Messrs. Gannett and Green.

it is necessary to hold the synchronization within approximately ½ of the width of one element. This gives 0.144 degree divided by 2 or 0.07 degree as the requirement within which synchronization should be held. By way of comparison it might be mentioned that the angular twist in a length of 6 ft. of 1-in. steel shafting operated at rated load is of about the same order of magnitude.

An ordinary four-pole synchronous motor when operating at full load, unity power factor, has an angular phase displacement of about 20 electrical degrees between the impressed and back e.m.f. This corresponds to 10 mechanical degrees since the motor has two pairs of poles. If this motor is operated at constant load and the line voltage is varied, the phase angle will decrease with increasing voltage, or when the voltage is held constant and the load is varied the phase angle will increase with increasing load. It is at once apparent therefore that the ordinary type of synchronous motor will not even approach the degree of precision required for the reason that any minute change in line voltage or load will cause variations in its phase angle of lag with respect to the impressed frequency of a far greater amount than 0.07 degree. Consider, however, a motor having 120 pairs of poles. Allowing 20 electrical degrees as the normal full load phase displacement, this would be equivalent to 20 divided by 120 or 1/6 degree mechanical phase displacement. Even this amount is over twice the required permissible displacement of 0.07 degree. Since the variation of the phase displacement is the important factor and not the absolute amount of displacement, it is evident that if the line voltage and load are held reasonably constant a synchronous motor with 120 pairs of poles should be sufficiently precise.

Another requirement in addition to close phase synchronization is regulation of the acceleration or deceleration of the generator at the transmitting end. Such regulation is required due to the fact that an appreciable time is taken for the transmission of the synchronizing current a distance of 220 miles (circuit length) between New York and Washington. The velocity of propagation over the cable was approximately 19,000 miles per second while that of the picture on the open wire of 285 miles circuit length was about 175,000 miles per second, the corresponding times of transmission being .0116 second and .0016 second, leaving a difference of .01 second approximately. Since the total permissible error in synchronization is .07 degree, it is reasonable to allow .02 degree as error due to acceleration regulation. Let a be the acceleration in degrees per second per second. Substituting in the formula $s = \frac{1}{2}at^2$ gives $.02 = \frac{1}{2}a(.01)^2$ or $a = 400$ degrees

per second per second or a little over one revolution per second per second. For comparison consider a ¼-h.p. unregulated shunt motor. If the line voltage increases 10 per cent, it will cause an increase in speed from 4 per cent to 8 per cent depending on the magnetic saturation in its field circuit. This increase in speed will take place in a half second or more depending upon the moment of inertia of the load. Thus the acceleration in the case of a 1060-r.p.m. speed would be much greater than one revolution per second per second.

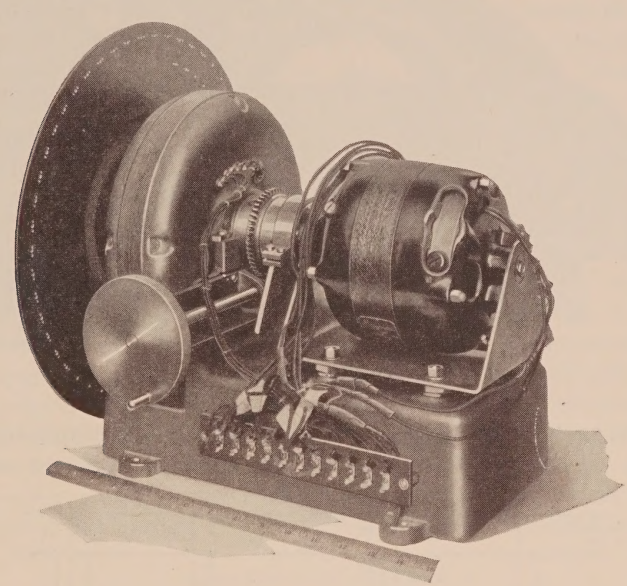


Fig. 1—Assembled motor

Since this problem of speed regulation is a separate one from that of the synchronization, the description of the regulating circuit is taken up later on.

Motor Design

In accordance with the phase displacement requirement as explained previously it was decided to build the synchronous motors with 120 pairs of poles, thus giving a frequency of 2125 cycles at 1062.5 r.p.m. which was the exact speed finally employed. For the sake of mechanical simplicity these machines were made of the variable reluctance type which gives one cycle per rotor tooth, thus requiring 120 teeth. The variable reluctance construction also simplifies the coil arrangement, the machine having only eight armature coils

instead of a separate coil for each tooth. Fig. 1 shows a photograph of the assembled motor and Fig. 2 an inside view of the stator and rotor.

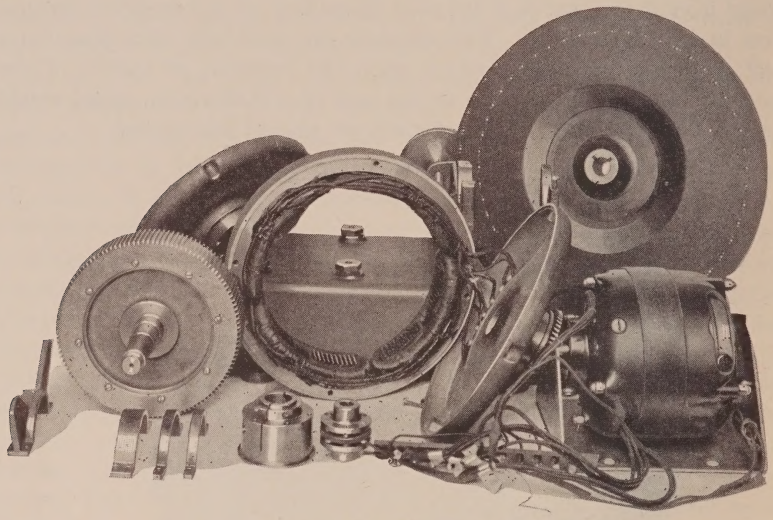


Fig. 2—Motor disassembled

In the preliminary experimental work two of these machines were directly connected (Fig. 3), permitting either machine to act as a

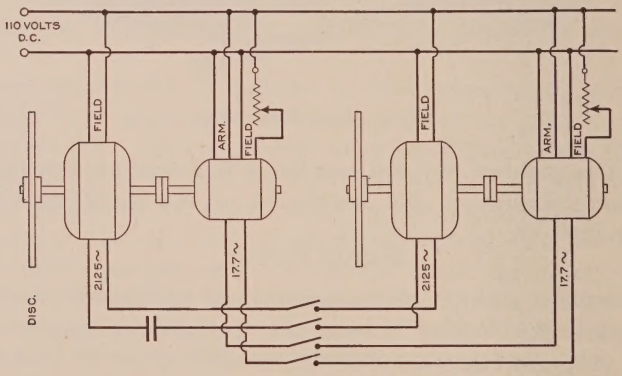


Fig. 3—Synchronization system over short wire line

synchronous motor loading down the other machine. Each machine was driven by a shunt d-c. motor having inherently poor regulation, the d-c. motors furnishing the power and the a-c. machines transferring

the variations from one d-c. machine to the other to hold synchronism in a completely two-way system. As was to be expected, it was found that the motors hunted badly at a frequency of about four cycles per second. In other words, instead of holding within a fixed electrical phase angle of 20 degrees the receiving motor oscillated throughout a phase angle of about $\pm$ 20 electrical degrees. This, of course, made the picture wabble back and forth across the aperture and was therefore unsatisfactory.

The ordinary method of preventing hunting by means of copper bars embedded in the pole faces was not practical on account of the large number of poles and limited space. The hunting trouble was cured by employing a series condenser between the motors using a value of capacity somewhat less than that required to tune the circuit. A rigid analytical treatment of this anti-hunting circuit is beyond the scope of this paper but its operation depends in general upon the curvature of the tuning curve due to the variation of the inductance of the machine with phase displacement. Since the condenser operates on the total inductance of the circuit, it is desirable to make the natural periods of oscillation of the two motors different. Otherwise a decrease in the inductance of one machine may be accompanied by a simultaneous and equal increase in the inductance of the other, thus leaving the total inductance unchanged and preventing the condenser from functioning. This was done by making one disk substantially heavier than the other.

The series condenser also neutralizes the greater part of the internal reactance of the motors, thereby increasing the steady state torque.

Framing of Picture

There was still one unsatisfactory feature in this system in that the motor at the receiving end could interlock in any one of 120 different angular positions whereas in order to get proper framing of the picture it must be synchronized at a particular angular position. For example, if the disk at the receiving end is exactly 180 degrees out with respect to the disk at the transmitting end, the observer will see the lower half of the picture on top; a dark space representing the dividing line between pictures and the upper half of the picture at the bottom. Similarly, if the disk is 90 degrees out at the receiving end, the lower quarter of the picture will appear on the top and the upper three quarters of the picture on the bottom. The disk at the receiving end may be brought into correct angular position by providing means for turning the entire motor through the necessary angle. It was found, however, that the rate at which the motor can be turned was limited

by the fact that if it were rapidly turned it would throw the motor out of step.

As an aid to framing, therefore, a second two-pole low frequency interlock was added to the system by providing the d-c. motors on each end with a pair of slip rings tapped to two opposite commutator bars. The d-c. shunt motors thus acted as converters furnishing 17.7 cycles at 1062.5 r.p.m. With this added feature on both the transmitting and receiving motors the process of synchronization was

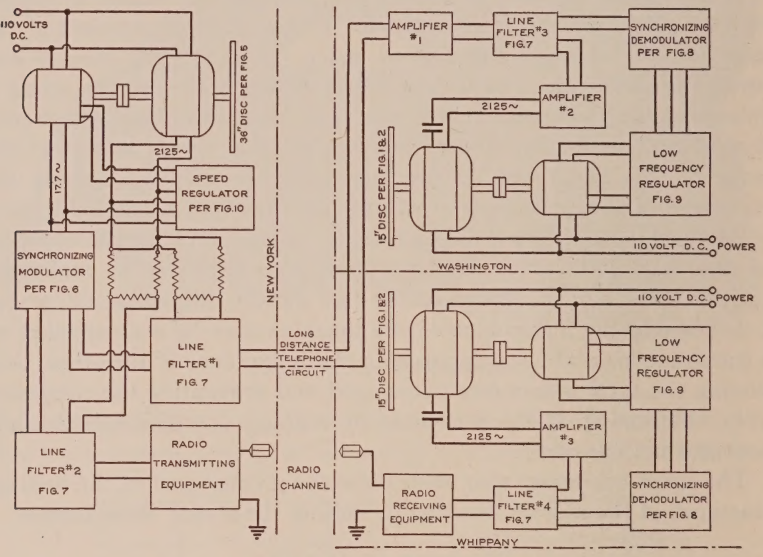


Fig. 4—Complete circuit of synchronizing system

first to close the 17.7-cycle circuit and adjust the field rheostat of the receiving motor until it came into step. Since this was a two-pole circuit there was only one angular position at which synchronization could occur. The high frequency synchronous machines were then connected together, thereby limiting the phase displacement to within .07 degree, as previously described. The high frequency motors in this system take the variation in load while the low frequency motor takes care of the steady constant component of load. Incidentally the addition of the low frequency synchronous motors greatly facilitated the synchronization of the high frequency motors inasmuch as it insured the proper initial speed. When the high frequency switch was closed there was merely a slight shift in phase angle to bring the receiving motor into step. The schematic circuit of the system thus far described is shown in Fig. 3.

Synchronization Over Long Lines

The above description explains the action of the synchronization system over lines of negligible impedance. In order, however, to secure similar results over a long distance telephone line or radio channel it is necessary to first attenuate the high and low frequencies to a power which can be safely applied to the transmitting end of the line and then amplify the power at the receiving end to restore it to the proper level. Fig. 4 shows the complete system employed.

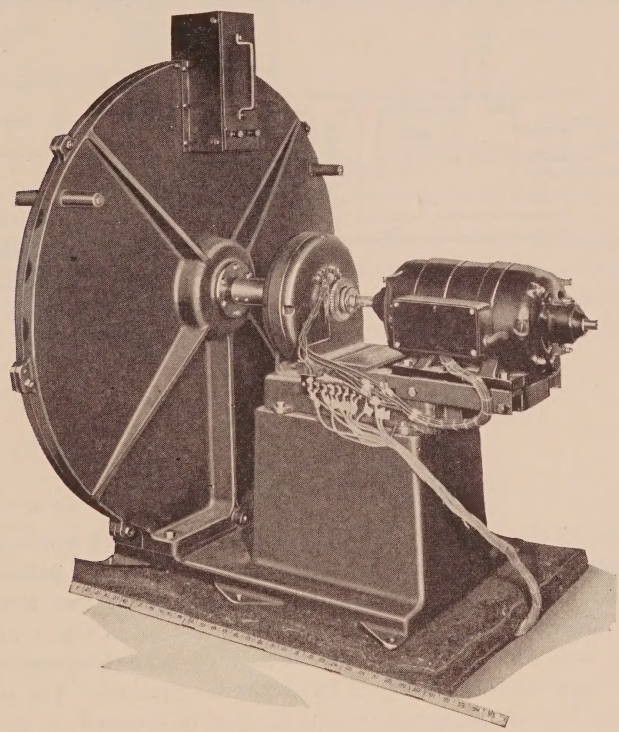


Fig. 5—Large scanning disc motor

While the high and low frequency machines on the transmitting end could have been designed so as to produce exactly the right power level, it was desirable, for the sake of interchangeability, to build the transmitting and receiving motor equipment of the same size. The output from the transmitting high frequency generator (shown in Fig. 2) when untuned was approximately 17 volts at 2125 cycles.

By means of a network this output was cut down to a level of 1 milliampere into 600 ohms impedance, the output impedance also being 600 ohms. This is a satisfactory level at which to transmit the high frequency, without inducing noise in adjacent wires in the telephone cables.

In the case of the low frequency interlock it was undesirable to attempt to transmit 17.7 cycles over a long distance line. The 17.7 cycles was therefore used to operate a polarized relay, the contacts of which modulated the output of a 760-cycle electro-mechanical oscillator [2] as shown in Fig. 6. In other words, the relay short-circuited

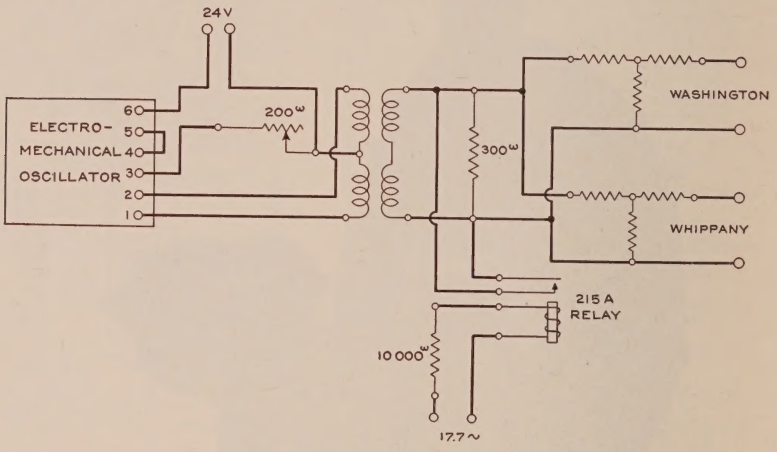


Fig. 6—Synchronizing modulator

the output of the oscillator alternate half cycles before application to the telephone line. Instead of using separate telephone pairs for the 2125-cycle and the modulated 760-cycle current, the two were combined by passing them through the line filter (shown in Fig. 7), thereby requiring only one pair for transmission of both frequencies. An identical network was employed for the radio channel. The problem of transmission of the synchronizing current is covered in the paper by Messrs. Gannett and Green and in the case of radio transmission in the paper by Mr. Nelson.

Receiving and Amplifying Circuits

Passing over this part of the problem, therefore, assume that the synchronizing currents have been obtained at the receiving end of the line. This power was delivered at a very low level, being about

[2] Described in the Bell Laboratories *Record*, March, 1927.

.3 of a milliampere into 600 ohms impedance, or 50 microwatts. It was then given a preliminary stage of amplification (amplifier No. 1, Fig. 4), passed through the line filter No. 3 (Fig. 7) and separated into 2125 cycles and 760 cycles modulated at 17.7 cycles. The 2125-cycle component was then amplified by two stages of amplification (amplifier No. 2) ending in push-pull 50-watt tubes and applied to

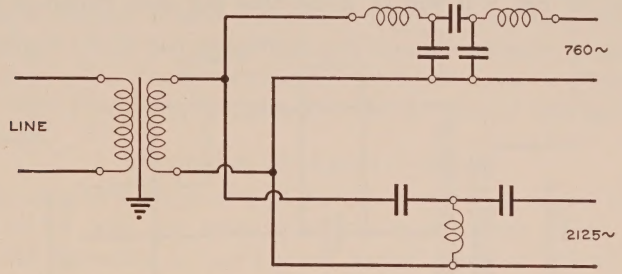


Fig. 7—Line filters for synchronizing frequencies

the high frequency motor. These amplifiers being of the standard type are not described. The terminal voltage on the output coil of the amplifier was made greater than that of the high frequency motor so that the power flow was normally from the amplifier to the motor.

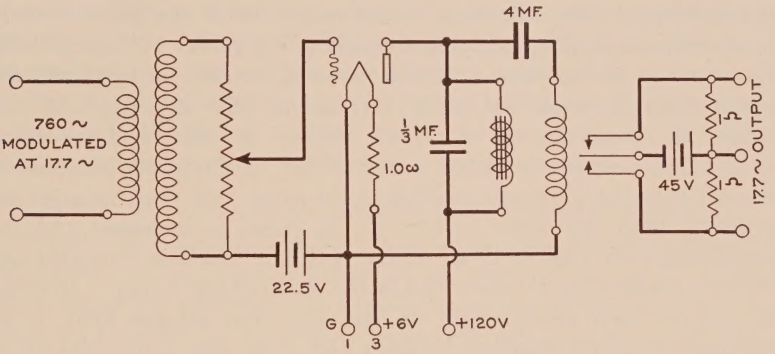


Fig. 8—Synchronizing demodulator

The anti-hunting condenser was retained between the amplifier and the motor.

In the case of the low frequency circuit the output from line filter No. 3 was received in the form of 760 cycles modulated at 17.7 cycles. This was passed through the demodulator (Fig. 8) which operated a polarized relay whose armature opened and closed its contacts at 17.7 cycles per second. The contacts of the relay provided square-wave low frequency current by interrupting power from a local battery

source. On account of the limited power output which the vibrating contacts could safely handle without sparking, it became necessary to amplify this low frequency output. While this would have been possible by the use of ordinary amplifier circuits, it was found preferable from the standpoint of economy of apparatus to apply the low frequency regulation through a field circuit of the receiving motor. Referring to Fig. 9 it will be noted that the plate circuit of the reg-

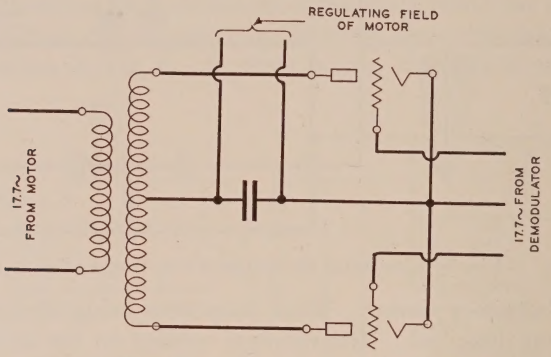


Fig. 9—Low frequency regulator

ulating tubes is supplied from the secondary of the transformer which is connected to the slip rings of the motor, while the grid circuit of these tubes is supplied with low frequency, low power 17.7 cycles from the contacts of the relay. As the motor is started up from rest the shunt field is weakened until the motor falls in step. At this point the frequency of the plate supply to the regulator tubes is identical with that supplied to the grids. If the phase relationship is such that the plates go positive at the same time that the grids are positive, then the space current of the tubes is increased and the regulating field (which is an aiding auxiliary field) is strengthened, thereby preventing a further rise in the speed of the motor. In other words, for each combination of load and line voltage there is an equilibrium phase position between the plate and grid voltages at which the corresponding regulating field current maintains the speed at the desired value.

Motor Operation

In actual operation the procedure was to first synchronize on the low frequency, and then on the high frequency circuit. The precise framing of the picture was then adjusted by rotating the motor by means of worm gearing through the necessary angle to center the image properly in the aperture. The high frequency current was of the order of 1.5 amperes at 2125 cycles with a terminal voltage of

100 volts at the high frequency motor. The power taken by the d-c. motor was approximately .8 ampere at 110 volts. The current through the regulating field controlled by the 17.7-cycle circuit was of the order of 20 to 40 milliamperes at 100 volts depending upon the phase position at which interlock occurred. It was found preferable to cut off the low frequency interlock feature after synchronization and framing had been obtained in order that irregularities in the time of contact closure of the relay might not produce changes in field strength of the d-c. motor which in turn would cause irregularities in power output. Such irregularities would give rise to phase shifts in the high frequency machine, thereby producing unsteadiness of the picture.

Operation on Radio Channel

In the case of transmission of the synchronizing current by radio instead of by wire the same apparatus is employed except that it was found necessary to use a much higher value of high frequency current in order to hold the high frequency motor in step, the current being approximately 4 amperes as compared to 1.5 amperes in the case of the other motors. This greater current was found to be necessary in order to hold the motor in step within the necessary phase angle of displacement, in spite of various types of interference picked up by the radio receiver, and associated circuits. This was mainly inductive interference from the picture and speech transmission sets arising from the fact that the synchronizing current was transmitted from New York to Whippany and picked up on a receiving set there, whereas the picture and voice current was transmitted from Whippany to New York. A certain amount of interference was also encountered from ship spark sets and static.

Speed Regulation of Transmitting Motor-Generator

As previously explained under "General Requirements" the essential requirement of the speed regulator at the transmitting end is to limit the acceleration to about one revolution per second per second, over intervals as small as .01 second. The ordinary type of centrifugally operated vibrating contact regulator keeps the motor continually accelerating and decelerating between an upper and lower speed limit and while such a system could theoretically be employed if the flywheel were made large enough, it was obviously preferable to employ a type of regulator in which the speed was inherently held constant without such acceleration and deceleration.

The regulating circuit employed is shown in Fig. 10. The complete theory of this regulating circuit is to be covered in another paper to be presented before the Institute. Briefly, the principle consists in

employing a sharply tuned circuit as the primary speed-controlling element resonating at a frequency slightly less than the frequency at which the machine is operated. A voltage from the high frequency generator is applied to this tuned circuit and thence to a detector tube which in turn operates on the grids of a pair of push-pull regulator tubes; these tubes controlling an auxiliary regulating field winding on the motor. The circuit also contains anti-hunting means, the

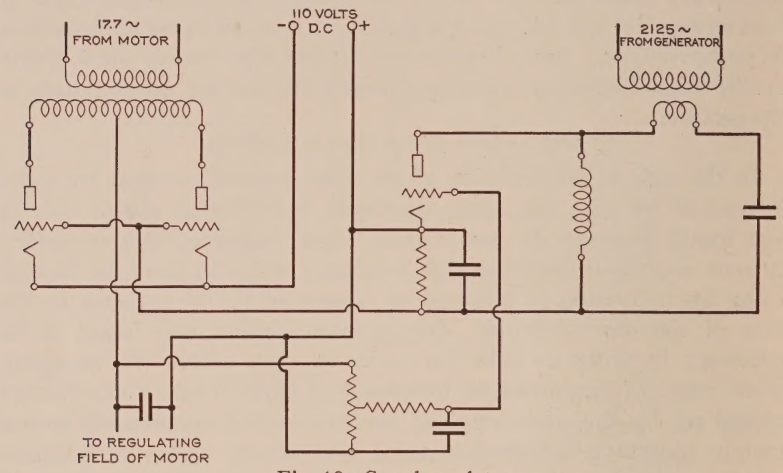


Fig. 10—Speed regulator

theory of which will be given in the later paper. Instead of applying this regulating circuit to the small 15-in. scanning disk motor shown in Fig. 3, it was decided on account of its greater flywheel effect to use the large 36-in. disk shown in Fig. 5 which was used for receiving the picture at New York. It therefore became the transmitter from the synchronizing standpoint for all of the other units although from the picture standpoint the big disk acted as a receiver.

Local Stations

In addition to the stations at Washington and Whippany there were three local stations in New York employing similar high and low frequency synchronous motors with 15-in. disks. These were controlled in the same manner except that first stage of amplification and the line filters were omitted. One station was employed for monitoring purposes, another operated a local transmitter, while the third operated the big grid receiver seen by the entire audience.

Wire Transmission System for Television[1]

By D. K. GANNETT and E. I. GREEN

American Telephone and Telegraph Company

SYNOPSIS: This paper deals with the transmission problems which were met and solved in connection with providing wire circuits from Washington to New York for the television demonstrations which took place on April 7, 1927, and following. For transmission of the television images a single transmission channel was set up combining the frequency ranges usually assigned to telegraph, telephone and certain carrier channels. The special line requirements were met so successfully that the television images transmitted from Washington were indistinguishable from those transmitted locally.

INTRODUCTION

A SYSTEM of television, to be worthy of the real meaning of the name, must be capable of operation over a considerable distance. Spanning this distance, there must be a connecting medium suitable for faithfully transmitting the television currents. This paper describes how the connecting medium was provided between Washington and New York for the recent television demonstrations,[2] by adapting to this purpose existing wire facilities of the Bell System.

Fortunately, wire facilities of the type which were available between Washington and New York had been utilized for some time to transmit simultaneously many telephone and telegraph messages, involving a frequency range more than ample for the television requirements, so that the transmission characteristics of the lines throughout the necessary range of frequencies were well known. The matter of providing a suitable channel to carry the television currents consisted, therefore, in throwing together the frequency ranges which had heretofore been utilized for providing a number of separate telephone and telegraph channels. In addition to providing this very wide band communication channel it was necessary to apply special distortion-correcting networks so that the overall channel would possess proper characteristics and also to take care to avoid introducing disturbances due to such things as line irregularities, noise, etc.

Due to the perfection of the transmission methods which were utilized, it was found that when the circuit was first established, in accordance with the requirements which had been deduced, the television images transmitted from Washington were indistinguishable in quality from those transmitted locally, this result being secured

[1] Presented at the Summer Convention of the A. I. E. E., Detroit, Mich., June 20–24, 1927.

[2] "Television," H. E. Ives; "The Production and Utilization of Television Signals," F. Gray, J. W. Horton and R. C. Mathes; "Synchronization in Television," H. M. Stoller and E. R. Morton.

without any deviation from the adjustments which had been worked out in the original design.

Requirements

General. The ideal requirement for a transmission line for television, or for that matter any other purpose, is, of course, that it introduce no distortion whatsoever, in which case there could be no question but that the television images obtained in the receiving apparatus after transmission over the long distance line would be identical with the image obtained with the transmission only over a distance of a few feet. Practical transmission lines, however, tend to introduce a certain amount of distortion and the less the allowable distortion which is specified the greater will be the cost of providing a proper line. Before going ahead with the matter of engineering the line required to transmit the television currents from Washington to New York it was, therefore, first necessary that the requirements be set. The requirements were made more severe than strictly necessary in cases where they were easy to meet.

Frequency Range. In any system for the electrical transmission of intelligence, the required frequency range is, in general, proportional to the speed of transmission. In the case of picture transmission or television, the speed of transmission may be expressed in terms of the number of picture elements which must be transmitted per second, where a picture element is the smallest unit area which it is intended to be able to distinguish in the received picture from its neighboring unit areas.

When the picture currents are transmitted in the most efficient manner, the frequency range necessary is approximately equal to half the number of picture elements which must be transmitted per second. A simple way of seeing this is to realize that as the picture elements are transmitted in sequence, the greatest possible rate of variation of detail is obtained when alternate picture elements are black and white. A complete cycle corresponds in this case, therefore, to the time interval required to transmit two picture elements.

According to this relationship this particular television system in which about 40,000 picture elements per second are transmitted should require a frequency range of approximately 20,000 cycles. As a matter of fact it was found by a laboratory test that due to certain characteristics of the apparatus a frequency range as great as this was ample, just detectable distortion being introduced in the reproduction of the human face when the range was narrowed to about 14,000 cycles. In providing the line circuit, however, extending the

frequency range to 20,000 cycles involved so little difficulty that it was decided to provide this very liberal frequency range.

In the particular television system which has been described the very low frequencies (below about 10 cycles) are suppressed. It was, therefore, not necessary that the line transmit these very low frequencies. The frequency range which the line should transmit was accordingly set as 10 cycles to 20,000 cycles.

Attenuation. Referring to still picture transmission, it has been found that variations of attenuation with frequency of several transmission units do not appreciably impair the quality of the picture. Since no great difficulty was anticipated in meeting closer limits, however, it was decided to set the limits for the variation of attenuation with frequency at $\pm$ 2 T U within the frequency range of 10 to 20,000 cycles.

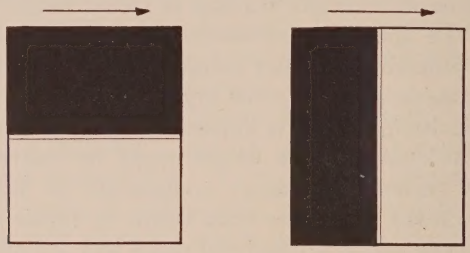
Phase Characteristics. A characteristic of wire lines, whose importance has been increasingly realized in recent years, is their phase characteristic. In speech transmission, transients due to unequal velocity of the different frequency components have been found to be an important consideration on some types of lines. In picture transmission and television, also, it is important that this phase distortion be controlled, as otherwise the image might be blurred due to the arrival of the various frequency components at different times. The type of transient which has been found to impair the quality of pictures is the type which is relatively rapid and the aim has been to make the phase characteristics such that those transients would be small.

The requirement with respect to phase for distortionless transmission is that β/ω be a constant where β is the phase change in radians for the entire circuit, and ω is equal to 2π times the frequency. β/ω is known as the "phase delay" or the steady-state time of transmission. $d\beta/d\omega$ is the time required for the transmission of the envelope of a wave whose components center closely about the frequency $\omega/2\pi$ and it will be referred to as the "envelope delay." Since it is more convenient to measure the envelope delay, the requirements were set up in terms of this quantity. When β/ω is constant, it is evident that $d\beta/d\omega$ is also constant. While the converse of this is not in general true, the conditions as actually encountered were such as to permit its use as a measure of the small variations involved.

The envelope delay characteristics of a number of circuits, which have been found to give varying degrees of transient on still pictures, have been measured. Also data were available from tests of picture transmission through filters and other networks whose delay charac-

teristics were known. From these various data, the permissible deviations of the delay characteristic for still picture transmission were determined, and dividing these figures by 50, the ratio of the rate of transmission in picture elements per second in the two cases, the limits for the television circuits were obtained. In this way it was decided to attempt to keep within ± 10 microseconds, if possible, with outside limits of ± 20 microseconds. Check tests of these limits were made with the television apparatus in the laboratory by transmitting the currents through various known networks, and noting the effect on the received image.

Unlike the attenuation requirements, the delay requirements for television are not the same over the entire frequency range, but are much more lenient in the lower frequency range, as was shown by experiments in the laboratory. A physical picture of the reason for this may be obtained by reference to Fig. 1.



Arrows show direction of motion of light spot

A B

Fig. 1

Fig. 1A shows a picture placed in position before the sending machine, consisting of a piece of cardboard the same size as the image-area which can be transmitted, the upper half of the cardboard being colored black, while the lower half is white. As has been explained in the paper by Messrs. Gray, Horton and Mathes, the picture is scanned by a spot of light which moves from left to right in successive lines, tracing 50 horizontal lines across the picture in one sixteenth of a second. The first 25 of the lines lie on the black and the remaining 25 on the light part of the picture. The process is repeated 16 times per second, each repetition of 50 lines giving one complete cycle of black and white. The frequency components in this case are multiples of 16 cycles. A transient which blurs the picture outline over a given number, n, of picture elements (downwards) corresponds to a time interval equal to the time of tracing n lines, *i.e.*, $n/800$ second.

Now consider Fig. 1B. Here the picture has been rotated 90 degrees.

In this position, a complete cycle of black and white is obtained with each line instead of with each 50 lines. The frequency components in this case are multiples of 800 cycles and bear the same relations to 800 cycles as the components spoken of above bear to 16 cycles. A transient which blurs the picture outline n picture elements (horizontally, this time) corresponds to a time interval of n forty thousandths of a second. Evidently the delay requirements are 50 times more lenient in the former case than in the latter so that the delay requirement at the highest frequencies, which determine the fine detail in the direction of scanning, is 50 times as severe as at low frequencies, which determine the fine detail in a direction perpendicular to the direction of scanning.

In the still pictures referred to, the transients extended in the direction of travel of the light spot and there were no transients analogous to those discussed here in connection with Fig. 1A. For this reason the delay limits determined from still picture transmission are the ones which apply to the higher frequencies. For the lower frequencies the requirements are obtained by multiplying the high-frequency requirements by 50. For these reasons, together with the result of a Fourier analysis of the picture current, the limits were set at $\pm$ 10 or $\pm$ 20 microseconds from 400 to 20,000 cycles. Below 400 cycles, the departures from the constant delay were permitted to be $\pm$ 500 or $\pm$ 1000 microseconds.

Noise. Another important requirement is that relating to the ratio of the picture currents to the extraneous interfering currents which may arise in the line from power induction and other sources. Early experience with the television apparatus showed that considerably more noise was permissible in the case of television than in the case of still picture transmission so that in this case comparison with the still picture transmission would result in an unduly severe requirement. This is thought to be explained by the fact that in the case of television the pictures are flashed before the eye 16 times per second and the effects of the extraneous currents occur on successive flashes in different positions, so that defects of one flash are corrected on the next.

A set of experiments was performed from which it was determined that if the ratio of average picture currents to average noise currents exceeded about 10 the results were satisfactory. In order to assure considerable margin above this figure, it was decided to make the average television current to be transmitted into the line 4 milliamperes.

Echoes. If two paths exist by which the currents may travel from the sending point to the receiving point, the length of the two paths

being different, a double image will be produced on the received picture, forming what may be termed visual echo. In the case of telephone lines, the echoes may exist on account of reflections between impedance irregularities in the circuit so that the currents arrive at the receiving point both by way of the direct transmission path and by way of a transmission path which includes an extra loop between two irregularities. If the echo is not greatly attenuated with respect to the main transmission, the result may be quite disturbing on the received picture. It has been found by experiment that the echo is too weak to be seen if it is more than 25 T U weaker than the main current and, accordingly, care was taken in setting up the New York-Washington circuit to avoid introducing echo paths of lower equivalent than this.

General Choice of Method

Two general methods are possible for transmitting the currents over the line circuits. One method is to transmit the currents directly without change of frequency. This method involves the transmission of the currents of the frequency range determined upon above, namely, from about 10 cycles to about 20,000 cycles per second.

The other general method is the carrier method, in which the television currents modulate a carrier current of suitable frequency and are thereby moved to another portion of the frequency spectrum prior to transmission over the line. At the receiving end of the line the carrier currents are then restored to the original frequencies of the television currents.

Several different schemes of carrier transmission are possible. The simplest is to modulate a carrier with the television currents and to transmit both side bands. This has the disadvantage of requiring the transmission of twice as wide a frequency range as that occupied by the original television currents. Another scheme is to transmit a single side band. A third possible scheme is to transmit both side bands for the lower frequencies and only one side band for the higher frequencies.

One advantage to be secured by the carrier method is that it lessens the severity of some of the line problems through avoiding the transmission of very low frequencies over the line circuit. At these frequencies the amount of noise found on lines is usually considerably greater than at the higher frequencies.

After weighing the relative merits of the carrier and direct transmission methods it was decided to make use of the latter because of its simplicity. An important factor in this decision was the successful development, for use in connecting the apparatus to the lines, of

transformers providing adequate transmission of the entire frequency range from 10 cycles to 20,000 cycles.

Arrangements for Television Circuits

Line Layout between New York and Washington. The layout of the wires between New York and Washington is shown in Fig. 2. The circuit over which the waves actually carrying the pictures were transmitted (marked Picture Circuit) consisted principally of a pair of copper wires 165 mils in diameter. At a number of places on the route the circuits were carried in cable as indicated in the figure. The total length of the television circuits was about 285 miles, of which 8 miles consisted of cables and the remainder of open wire.

Transpositions. As the circuits employed were originally designed for voice-frequency operation only, except for a section at the New York end, it was necessary to add transpositions to them to prevent interaction with adjacent circuits at the high frequencies involved in the television transmission. The high-frequency currents were thus prevented from passing over into the adjacent circuits which would have resulted in irregularities in the attenuation, line impedance and phase shift characteristics of the circuit.

Incidental Cables—Loading. Any appreciable length of non-loaded cable included in an open-wire television circuit has certain very objectionable effects. The impedance irregularities introduced by the cable destroy the uniformity of the line attenuation, impedance and phase shift characteristics as a function of frequency, and tend to produce echoes as described above. Types of loading developed for use on incidental cables occurring in circuits employed for carrier telephone and carrier telegraphy operation [2] were employed to reduce these effects to a minimum. This carrier loading is designed so that when used on No. 13 A. W. G. cable circuits it provides an impedance which approximates very closely that of the open wire. With a spacing of about 930 feet between loading coils, this loading has a nominal cut-off of about 45,000 cycles, which corresponds to an effective transmission range extending up to about 36,000 cycles. In order to obtain a close match between the impedances of the open-wire and the cable pairs, thereby avoiding impedance irregularities, 13-gage pairs were selected for the television circuits in all of the cables.

The length of the submarine cable under the Hackensack River (about 1100 feet) was too great to permit the use of regular carrier

[2] "Development and Application of Loading for Telephone Circuits," T. Shaw and W. Fondiller, *Journal A. I. E. E.*, Vol. XLV, pages 253–263, March, 1926.

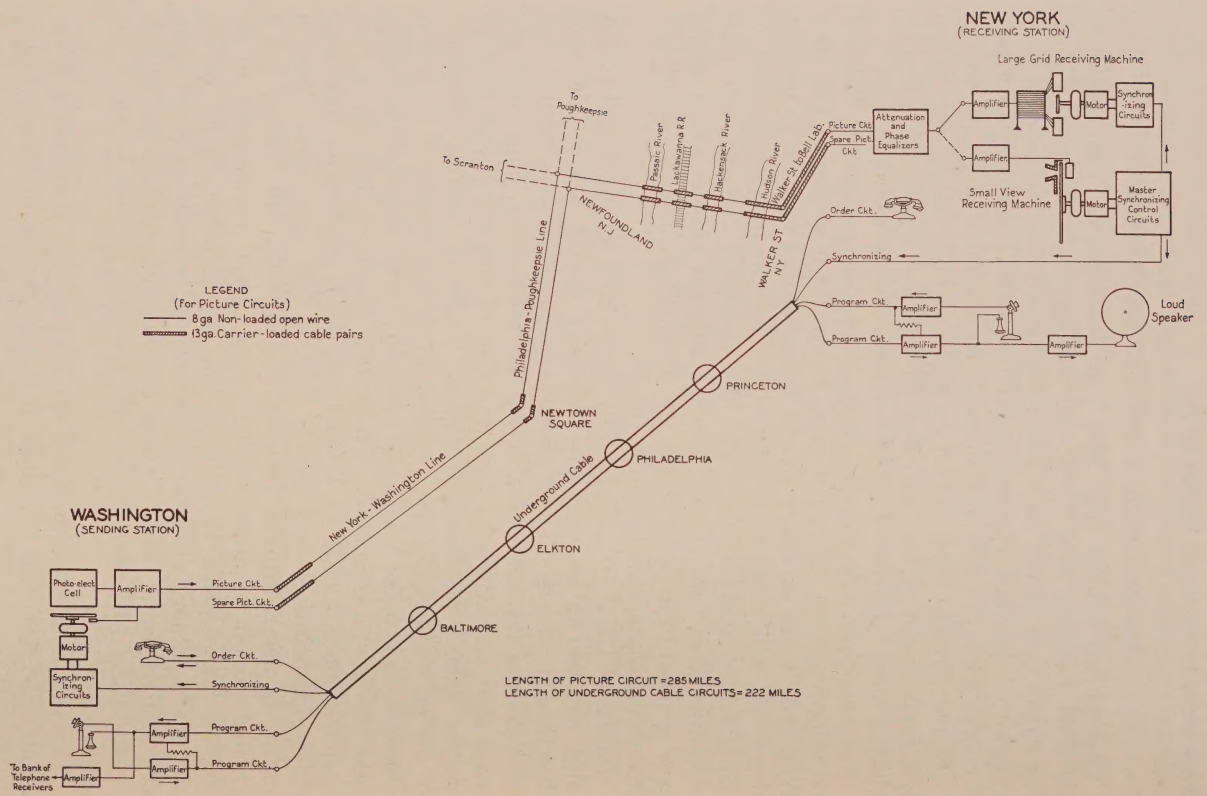


Fig. 2—Schematic diagram of circuits for television demonstration

loading, and a special loading arrangement having a slightly lower cut-off was, therefore, designed for this cable.

Equalization

Requirements. The requirements for the lines were stated earlier. In order to meet these overall requirements it was necessary to apply special forms of distortion-correcting networks.

Weather Changes. The above requirements applied, of course, to

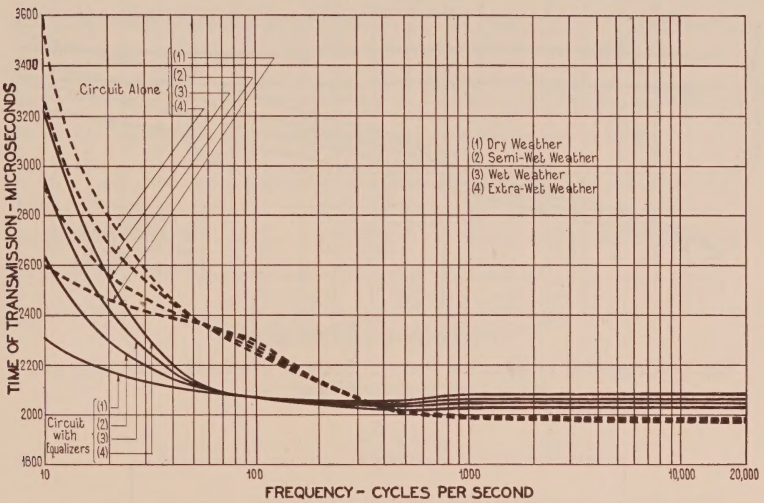


Fig. 3—Computed phase delay (β/ω) of television circuit with and without equalizers

all of the various weather conditions to which an open-wire circuit is subject. Due to the changes in the leakage conductance occurring at the insulators, the attenuation of an open-wire circuit varies with changing weather conditions. This change is particularly important at the higher frequencies. At 20,000 cycles, for example, the attenuation of a 165-mil open-wire pair may vary as much as 40 per cent for a change from dry weather to extra wet weather. For the circuit between Washington and New York this represents a possible attenuation change of about 10 T U, or a change of 10 to 1 in the magnitude of the received power. At 1000 cycles, the effect of wet weather is comparatively small, so that the net effect of the weather variations is to change the requirements for the attenuation equalizers. The phase shift introduced by an open-wire pair likewise varies to some extent with changes of weather, although the percentage variation is much smaller than in the case of the attenuation. In view of

these variations in the line characteristics it was decided to provide basic networks which would equalize for dry weather conditions, and to make available, in addition, several steps of equalization which would compensate for changes in the direction of wet weather.

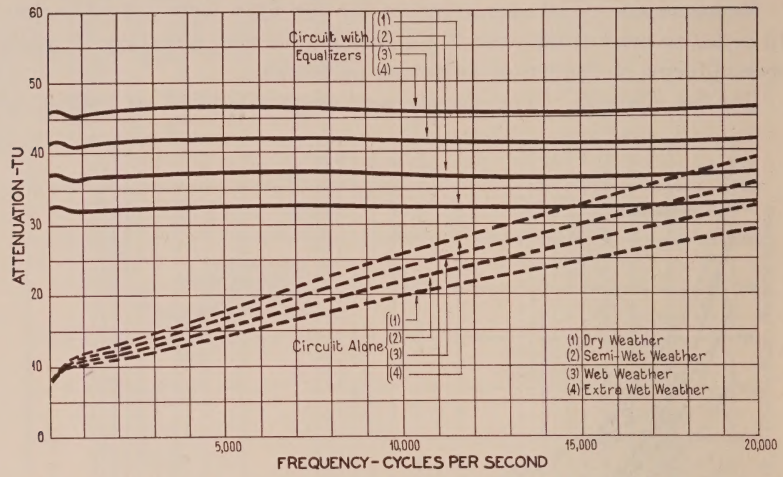


Fig. 4—Computed attenuation characteristics of television circuit with and without equalizers

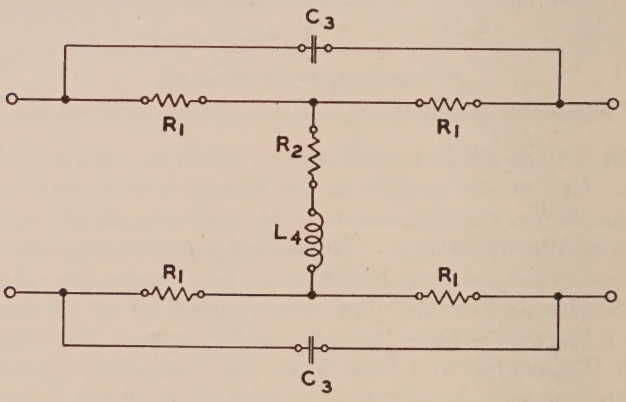


Fig. 5—Low-frequency equalizing network (dry and wet weather)

Low-Frequency Network. Computed curves of attenuation and phase delay for the overall Washington-New York circuit without correcting networks are shown in Figs. 3 and 4, respectively. The

form of the dry weather attenuation curve suggested the use of two correcting networks, one for low frequencies, the other for high frequencies. The network which was designed to equalize the at-

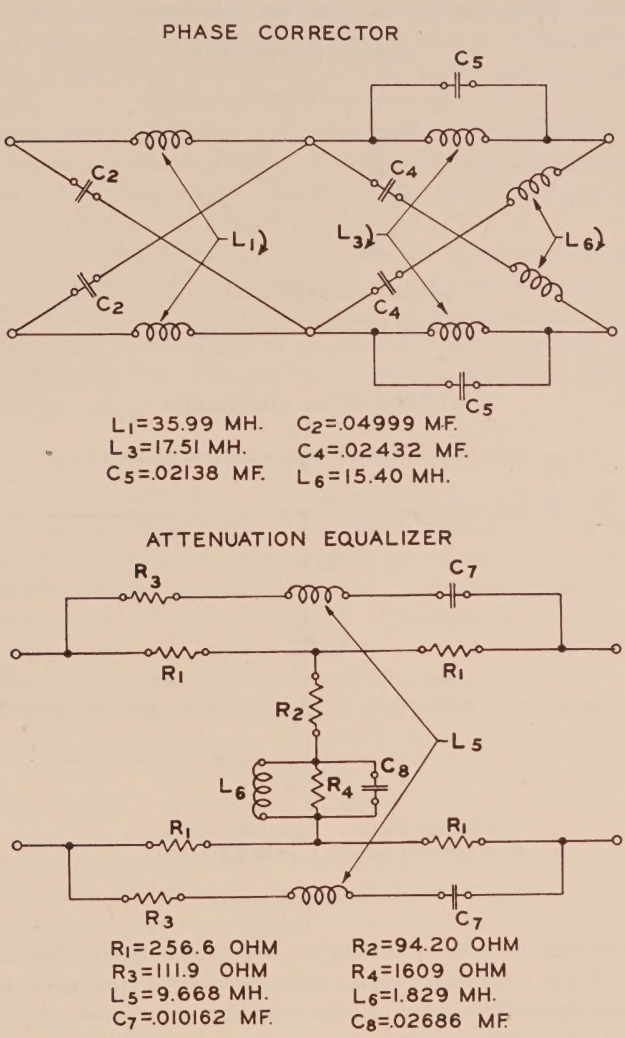


Fig. 6—High-frequency equalizing networks (dry weather)

tenuation at the lower frequencies is illustrated in Fig. 5. This network, in addition to equalizing the low-frequency attenuation, was made to provide sufficient correction for the low-frequency phase characteristic. It also proved satisfactory for all weather conditions.

High-Frequency Network for Dry Weather. The complete network for the correction at high frequencies under dry weather conditions was designed in two parts, an attenuation equalizer and a phase corrector. These two structures are illustrated in Fig. 6. The

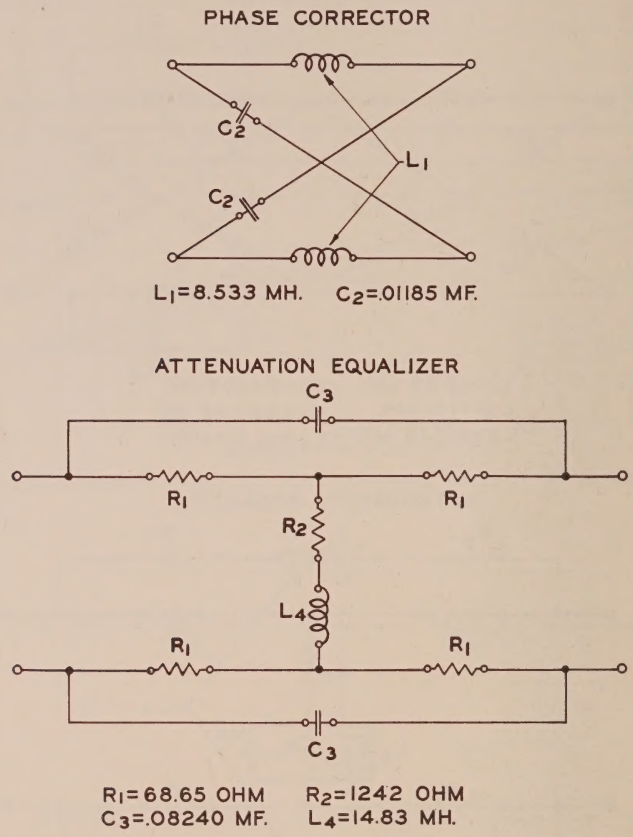


Fig. 7—Weather change equalizing networks

computed dry weather attenuation and phase delay resulting with the use of the combined low-frequency and high-frequency networks are illustrated in the curves of Figs. 3 and 4. It will be noted that the corrected attenuation curve is constant to within approximately $\pm$ 0.3 T U, while the corrected time of transmission falls well within the prescribed limits.

Weather Change Networks. Correction for the additional distortion introduced by changes from dry to wet weather was provided by three

additional networks which were, for convenience, of identical design. The results obtained by using one, two or three of these networks were made to correspond, respectively, to three assumed weather conditions which may be designated semi-wet, wet, and extra-wet. These three conditions were determined upon the basis of the range of leakage conditions which exist on open-wire lines under different weather conditions.

The attenuation equalizing and phase correcting networks for one of these steps are illustrated in Fig. 7, while the computed attenuation and phase delay obtained by the use of the three different steps of weather correction are shown in Figs. 3 and 4.

The networks described above are of the "constant-resistance" type, whose characteristic impedance is a pure resistance at all frequencies.[3] These networks are designed to be connected in series. The methods used in the design of the networks involve a large amount of mathematical theory, a discussion of which is not necessary for the purposes of this paper.

Synchronizing and Voice Circuits

So far the discussion has dealt only with the problem of transmitting the television currents. In addition to this, there is required the transmission of voice currents and of synchronizing currents. It is entirely feasible to transmit these currents together with the television currents over a single circuit. However, for the purpose of simplification, separate facilities were employed in the television experiments for picture, voice and synchronizing currents.

The diagram in Fig. 2 shows the circuits which were actually provided for the demonstrations. It will be seen that in addition to the two picture or television circuits, there were provided a synchronizing circuit, a four-wire "program" circuit, and an order circuit.

The method of synchronizing the sending and the receiving machines has already been described in the paper by Mr. Stoller. It requires two currents, one having a frequency of about 18 cycles and the other about 2125 cycles. In order that an ordinary telephone circuit might be used for this purpose, the lower frequency was made to modulate by means of a telegraph relay, a carrier current having a frequency of about 750 cycles per second. An amplifier-detector at the receiving end of the synchronizing system demodulated the 750-cycle current, delivering 18 cycles to the television apparatus.

The requirements for the synchronizing circuit were that it must

[3] Partially described in U. S. Patent No. 1,603,305 to O. J. Zobel.

transmit a narrow range near 750 cycles, and the single frequency of 2125 cycles. These synchronizing frequencies are determined by the speed of the motors, which was chosen so that the frequencies would be suitable for transmission over two channels of a voice-frequency carrier telegraph system,[4] but later it was found more convenient to use a separate telephone circuit.

The circuits labeled "program" provided telephonic communication between the observer at New York and the person being viewed at Washington. A loud speaker was also connected to this circuit at New York to transmit the voice to the audience when the large grid receiving arrangement was employed. A special by-passing connection was provided between the amplifiers at the terminals of the circuit so that speech from the local microphone could be heard as well as speech from the distant city.

The order circuit was for the purpose of providing communication between the engineers operating the television apparatus.

Line Measurements

In order to determine that the circuits set up as outlined above were satisfactory, their overall characteristics were measured. Certain matters of interest in this work are noted below.

Measurements of Envelope Delay. In order to measure the envelope delay to an accuracy comparable to the requirements for the lines, it was necessary to develop special apparatus. Fig. 8 shows in schematic form the circuits of the apparatus designed for this purpose. The apparatus measures not the absolute envelope delay of a circuit, but the relative delay of one circuit at any frequency from about 600 cycles to 20,000 cycles or more with respect to the delay on the other circuit at a fixed frequency.

The functioning of the apparatus may be briefly described as follows: Simultaneously into each line there was transmitted a carrier current, each carrier being modulated by 250-cycle current from the same oscillator. The modulation was accomplished in push-pull vacuum tube circuits so that the undesired products of modulation were eliminated by balance. The carrier on the line under measurement was adjusted to the frequency at which a measurement was desired, and the carrier on the other circuit, used for reference, was kept at a fixed frequency of 5100 cycles.

At the receiving point identical circuits were provided for amplifying

[4] "Voice-Frequency Carrier Telegraph System for Cables," B. P. Hamilton, H. Nyquist, M. B. Long and W. A. Phelps, *Journal A. I. E. E.*, Vol. XLIV, pages 213–218, March, 1925.

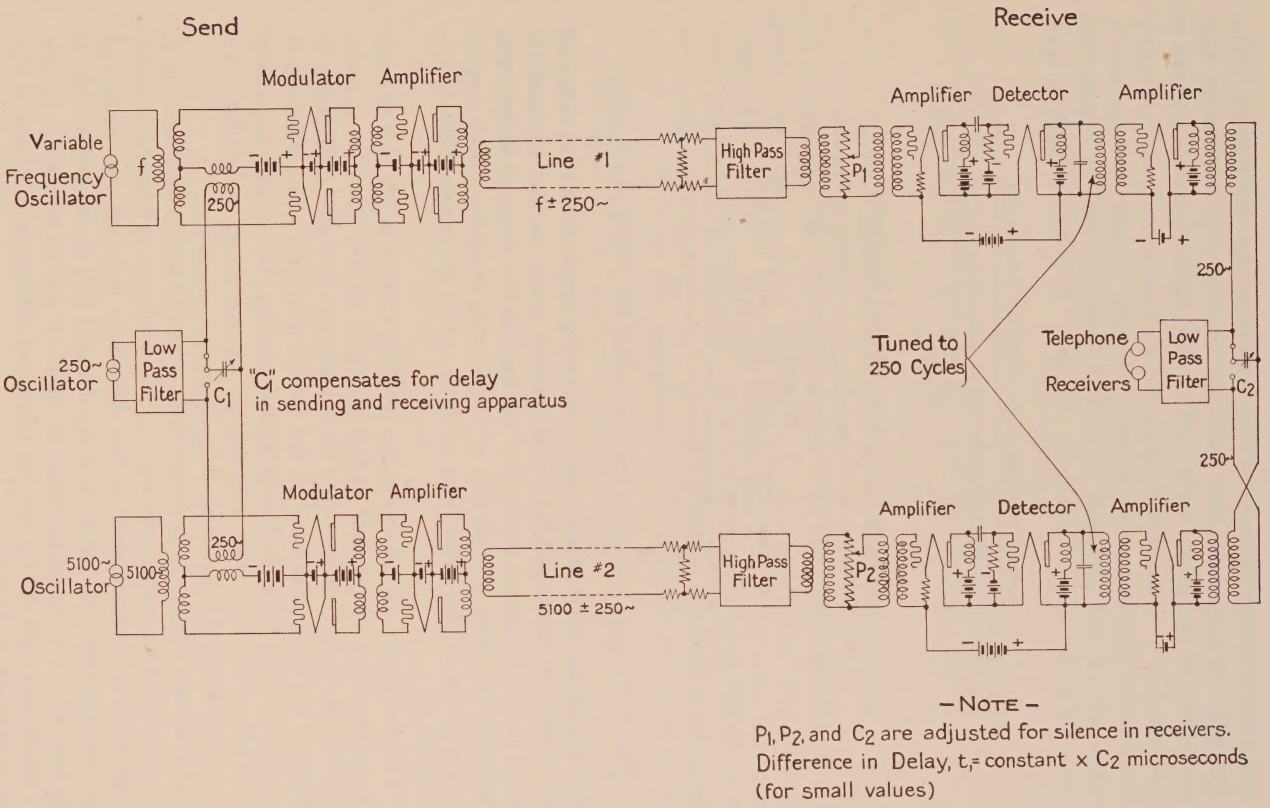


Fig. 8—Arrangements for measuring envelope delay of television circuits

and demodulating the received currents from the two circuits. The 250-cycle outputs from the two sets of receiving apparatus were connected in opposition to a pair of telephone receivers through a low-pass filter. Potentiometers P_1 and P_2 were provided for adjusting the relative intensities of the two 250-cycle output voltages and a condenser C_2 was arranged so that it could be used to change the phase of either of the 250-cycle voltages. It is evident, then, that

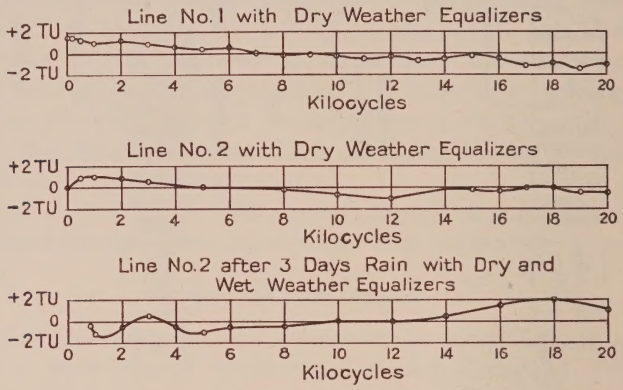

Line No. 1 with Dry Weather Equalizers
+2 TU
0
-2 TU
0 2 4 6 8 10 12 14 16 18 20
Kilocycles
Line No. 2 with Dry Weather Equalizers
+2TU
0
-2TU
0 2 4 6 8 10 12 14 16 18 20
Kilocycles
Line No. 2 after 3 Days Rain with Dry and Wet Weather Equalizers
+2TU
0
-2TU
0 2 4 6 8 10 12 14 16 18 20
Kilocycles

Fig. 9—Measured attenuation characteristics of line circuits plus equalizers

by making suitable adjustments the two voltages could be adjusted to exactly the same intensity and opposite phase so that no sound is heard in the telephone receivers. As long as the value of C_2 is small, the envelope delay of one line at the carrier frequency with respect to the delay of the other line at 5100 cycles is proportional to the value of C_2.

The condenser C_1 shown at the sending station is for the purpose of introducing a phase shift in the 250-cycle current of either channel relative to the other in order to compensate for the differences in delay of the apparatus itself at the two frequencies. The value of C_1 was determined by experiment before moving the sending apparatus to Washington and was adjusted to its calibrated value for each frequency when the oscillator frequency was adjusted.

The measurement of the phase shift of the 250-cycle current, which is transmitted by means of a carrier over a circuit as described above, is actually a measurement of the difference between the phases of the two received side-band currents situated 250 cycles either side of the carrier. The envelope delay is equal to $\Delta\beta/\Delta\omega$ where $\Delta\omega$ equals 2π times 500, and $\Delta\beta$ equals the measured difference in phase of the two side bands in radians.

Measurements and Performance. How well the requirements which were set up earlier were met by the lines and the distortion-correcting networks is shown in Figs. 9 and 10. The attenuation characteristics

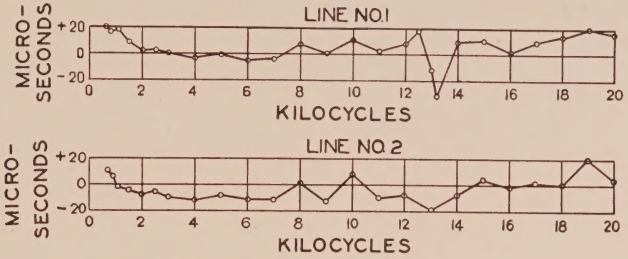


Fig. 10—Measured envelope delay of line circuits plus equalizers

are well within the established limits, and the phase characteristics show only a single slight departure for one circuit in a very narrow range of frequency. It is of interest, in view of the fact that the distortion-correcting networks were designed and built before any measurements were made on the lines they were to fit, that no changes or adjustments were found to be necessary in the networks, in order to obtain these characteristics.

Comparison of the television images obtained from transmission over the line with those obtained from transmission from one side of the room to the other, showed that no difference in quality could be observed.

Radio Transmission System for Television[1]

By EDWARD L. NELSON

Bell Telephone Laboratories, Incorporated

SYNOPSIS: Starting from the general requirements imposed on the transmitting medium, this paper discusses the engineering of a radio system for television purposes and describes the radio facilities actually employed for the recent Bell System demonstration. The tests to which the system was submitted to determine its suitability are outlined and the measured frequency-response characteristics are shown. An interesting phenomenon due to multi-path transmission, the production of positive and negative secondary images, is reported. A brief series of experiments concerned with the transmission of both voice and image "on a single wavelength" is also described.

IN other papers of this symposium, the general nature of the television problem has been discussed, the scope of the recent Bell System demonstration has been outlined, terminal apparatus for television has been described, and the general requirements to be met by the transmitting agency have been formulated. This paper is concerned with the problem of engineering a suitable radio system for television purposes and with a description of the radio facilities actually employed for the demonstration.

REQUIREMENTS IMPOSED ON THE RADIO SYSTEM

The radio experiments were conducted from the Bell Telephone Laboratories' Experimental Station 3XN at Whippany, New Jersey. Between this point and the main Laboratories Building at 463 West Street, New York City, some 22 miles distant, three separate communication channels were required—one for the picture, a second for synchronizing, and a third for speech and music. The demonstration being of a three-cornered nature involving New York, Washington and Whippany, it was deemed to be highly advantageous to transmit the necessary synchronizing currents for both the wire and radio systems from a master generating set located in the auditorium of the West Street Building. Hence the synchronizing channel was required to operate from New York to Whippany, while the picture and speech channels necessarily transmitted in the reverse direction.

From the radio standpoint, the problem presented for solution may be described as follows:

1. There is given television transmitting and receiving apparatus designed to work into and out of specified impedances at stated signal

[1] Presented at the Summer Convention of the A. I. E. E., Detroit, Mich., June 20–24, 1927.

energy levels. Signal components ranging in frequency from 10 to 20,000 cycles must be transmitted with as little discrimination with respect to either amplitude or phase as reasonable design practices will permit. It is required that a suitable radio system be designed to afford satisfactory transmission between terminals when operated under prevailing conditions with respect to static, other radio traffic, and local electrical disturbances. The maximum allowable "noise" level is probably somewhat arbitrary but it has been found that if the ratio of signal to interference current is 10:1 the results are satisfactory. The variation of amplitude with frequency should probably not exceed $\pm$ 2 TU at any point in the required signal band. The equivalent of the circuit must be substantially constant; in other words, no fading effects can be tolerated. In this respect a variation of perhaps 3 TU is the maximum allowable.[2]

2. For synchronizing purposes, a second channel must be provided to transmit 17.7 and 2125 cycles, the impedances and the signal energy levels at both ends of the circuit being known. The grade of transmission required in this case is probably considerably lower than that needed for the picture circuit but stable operation must be assured.

3. Arrangements must also be made for a high quality telephone channel to transmit speech and music for loud speaker reproduction.

4. All of these channels must, of course, be capable of operating simultaneously without mutual interference and without effect on established radio services.

Preliminary Survey

In the vicinity of New York, an assignment of this type is surrounded with unusual difficulty due to the serious congestion which exists in the ether. Operations were started, therefore, by undertaking a survey of available frequency bands at periods of the day during which transmission might be required.

The pioneering nature of the project and the character of the apparatus available led to an early decision to base the system on the transmission of the carrier and both sidebands. Since the upper limit for the signal was specified as 20,000 cycles, an interference-free band somewhat greater than 40,000 cycles in width was, therefore, required. The unusual width of this band indicated the desirability of fixing upon a relatively high carrier frequency. No readily available

[2] Definitely agreed on limits were essential to proper coordination of the various development activities and figures of the order mentioned were assumed for design purposes.

substitute for the ordinary type of tuned circuit was at hand and such circuits discriminate seriously against side frequencies differing by more than a few per cent from the frequency to which they are adjusted.

The results of the survey disclosed two bands somewhat wider than that required centering approximately about 1575 and 1750 kilocycles. It was also conclusively demonstrated that the operation of the synchronizing channel at a frequency above the broadcasting

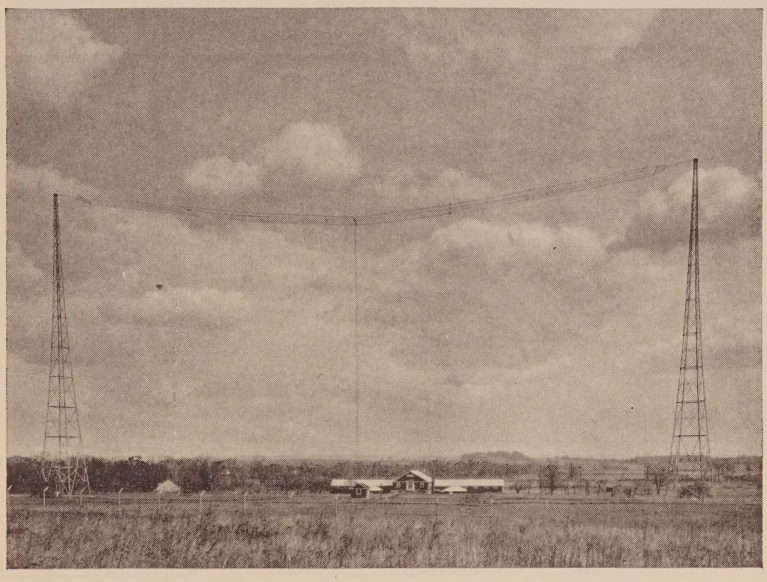


Fig. 1—General view of the Whippany Station, 3XN

band was entirely out of the question. With two broadcasting stations located in the immediate neighborhood, one producing a field strength of perhaps 50 millivolts per meter and the other several volts per meter, the operation of a third transmitter on an adjoining frequency with the maximum obtainable separation between antennae, resulted in an almost continuous interference spectrum. It was decided, therefore, to transfer the synchronizing channel to a frequency of the order of 185 kilocycles, which would be sufficiently remote to remove interference from this source, and to make further studies in the regions about 1575 and 1750 kilocycles based on transmission from Whippany. No difficulty was anticipated in making suitable arrangements for the speech channel on account of the narrower band required and the well-known nature of the problem.

The Whippany Station, 3XN

A general view of the station site at Whippany is shown in Fig. 1. The property consists of some 47 acres. The main laboratory building, which is located near its center, is a two-story structure affording approximately 18,000 square feet of floor space. The principal antenna system involves two 250-foot steel towers with a suitable buried ground system, which is placed some 500 feet out in front of the building in order that the latter may be clear of the denser portion

Fig. 2—Operating room at 3XN. Transmitter for television channel on the right. Power supply unit and radio transmitter for the speech channel in the center and on the left, respectively.

of the electric field. This antenna was assigned to the picture channel. For the voice channel, a separate structure located 500 feet in the rear of the laboratory building or approximately 1000 feet from the other was employed. The original supports in this second case were 60-foot wooden masts but subsequently metal topmasts were added, bringing the total height to 100 feet. Both antennae were energized by means of radio-frequency transmission lines. The antenna tuning and coupling apparatus was housed in small buildings placed under the center of each antenna, that for the larger structure having a copper roof which was securely connected to the ground network.

This type of installation is thought to afford a number of advantages. By separating the building and the antenna it becomes a much simpler matter to control the electrical factors which enter into the design of the latter. Removing the building from the field tends toward

reduced dielectric and eddy current losses and consequently toward higher antenna efficiency. The resulting improvement may be expected to more than compensate for the slight loss in the line, which should not exceed 3 per cent. Removing the field from the building is equally advantageous in that it simplifies the precautions which normally have to be taken to prevent the radio-frequency energy from affecting the performance of audio amplifiers and other supple-

Fig. 3—Television transmitting apparatus in the studio at Whippany

mentary vacuum tube apparatus. The most serious disadvantages arise from the fact that the antenna must be tuned and the current in it measured at a point remote from the transmitting apparatus proper.

In spite of the fact that the station building was not directly under either antenna, some difficulty was anticipated from radio-frequency fields produced within the transmitting equipment due to the relatively high amplification employed with the photoelectric cells. In order to minimize trouble of this nature a special shielded studio was con-

structed in one of the wings of the building to house the television terminal apparatus. Walls, ceiling and floor were completely covered with No. 24 gage sheet copper lapped about one inch and carefully soldered. The windows were covered with fine copper gauze. The door was covered with sheet copper which was carried around the edges so that in closing it made a firm wiping contact with the surrounding frame. Circuits for lighting and miscellaneous power service were led in through two specially constructed transformers fitted with grounded copper shields between the primary and secondary windings. The picture circuits leading to the radio transmitter, the microphone circuits, and the necessary studio signal and control circuits were run in lead cable and in most cases were brought into the room through suitable radio-frequency filters enclosed in metal boxes attached to the copper sheathing. In order to avoid the possibility of the heavy current leads to the arc bringing in radio-frequency energy, and to eliminate the noise and heat from the arc, provision was made for mounting the latter in its metal cabinet outside of the room. The circular opening through which the light beam was projected into the room was protected by the lamp cabinet which was also grounded to the sheathing. Satisfactory acoustic conditions within the studio were obtained by applying celotex wall board over the copper and by the use of suitable floor coverings.

Transmitting and Receiving Apparatus

For the television channel, arrangements were made to install a standard Western Electric 5-B Radio Broadcasting Transmitter and to modify it for the purpose. This transmitter is a 5-kilowatt unit (carrier output without modulation) designed for high quality telephone transmission in the 500–1500-kilocycle band. It will transmit signal components ranging from 50 to 5000 cycles without noteworthy discrimination. At 30 cycles and at 10,000 cycles there is some loss in efficiency and beyond these points the characteristic curve falls rapidly. The necessary changes, therefore, involved both the radio and audio circuits, the latter phase of the problem being perhaps the more difficult.

The schematic circuit of the modified transmitter is shown in Fig. 4. The revised radio frequency circuits were very similar to the standard arrangement, the changes mainly affecting the magnitudes of various coils and condensers. The output circuits were, of course, redesigned to meet the conditions imposed by the transmission line. The circuit was of the master oscillator—modulating amplifier—power amplifier type. The master oscillator employed a 50-watt tube operating in a

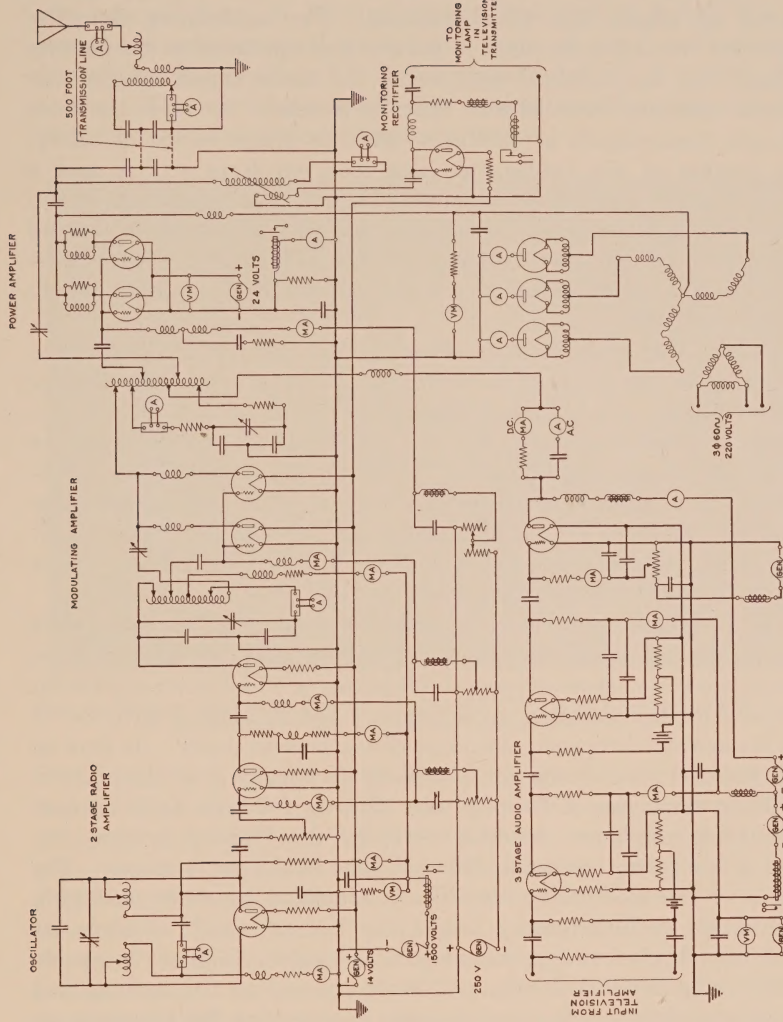


Fig. 4—Schematic of radio transmitter for television channel

circuit designed to afford a high degree of stability. This was connected to the input of the modulating amplifier through two radio-frequency stages, also employing 50-watt tubes. These two stages precluded the possibility of the oscillator frequency being appreciably altered by effects due to modulation. The modulating amplifier employed two 250-watt tubes in parallel and operated on the Heising system. In the standard equipment, the audio stages involve one 50-watt tube and two 250-watt tubes in parallel. To meet the more rigorous requirements of television with an ample factor of safety, this portion of the transmitter was removed from service and a specially constructed three-stage amplifier was substituted. As shown in the drawing, the latter consisted of two 50-watt resistance-coupled stages and a final power stage based on a 5-kilowatt water-cooled tube which raised the signal currents to a power level of approximately one half kilowatt.

In order that it might be possible to check the performance of the radio transmitter under all operating conditions, a suitable monitoring rectifier was constructed and coupled to the output circuit of the radio-frequency power amplifier. A circuit was run back to suitable switches on the television control panel so that either the output of the photo-electric cell amplifiers or the rectified output of the radio transmitter could be impressed on the pilot lamp of the television transmitter. By comparing the two images, it thus became a relatively simple matter to detect any serious maladjustment in the radio apparatus.

The problem of providing a suitable transmitter for the speech channel was rendered quite simple by the fact that at the time there was in process of development at Whippany a 50-kilowatt equipment intended for broadcasting applications. The detailed description of this transmitter is beyond the scope of the present paper. It may be said, however, that it consists of a piezo-electrically controlled master oscillator employing a 50-watt tube directly followed by a 50-watt modulating amplifier. Modulation is by the Heising system, employing one 50-watt and one 250-watt tube in the audio stages. The output of the modulating amplifier is amplified by three push-pull, neutralized, radio-frequency stages the last of which employs six water-cooled tubes at approximately 17,000 volts. This set is capable of delivering 50 kilowatts (unmodulated carrier) to the antenna and during modulation instantaneous peaks approaching 200 kilowatts are attained.

The radio receiver employed at Whippany for the reception of the synchronizing signals at 185 kilocycles presents no features of unusual interest. A double-tuned input circuit was used followed by three

stages of radio-frequency amplification, a detector, and two audio stages of conventional design employing transformer coupling. No serious difficulty was encountered in obtaining ample selectivity to insure satisfactory operation in the face of the strong local signals but care was necessary in locating the receiver and in laying out the antenna in order to avoid the inductive type of interference which is almost always experienced in the immediate vicinity of a large radio station. The receiving antenna was located approximately 700 feet from the two transmitting radiating systems.

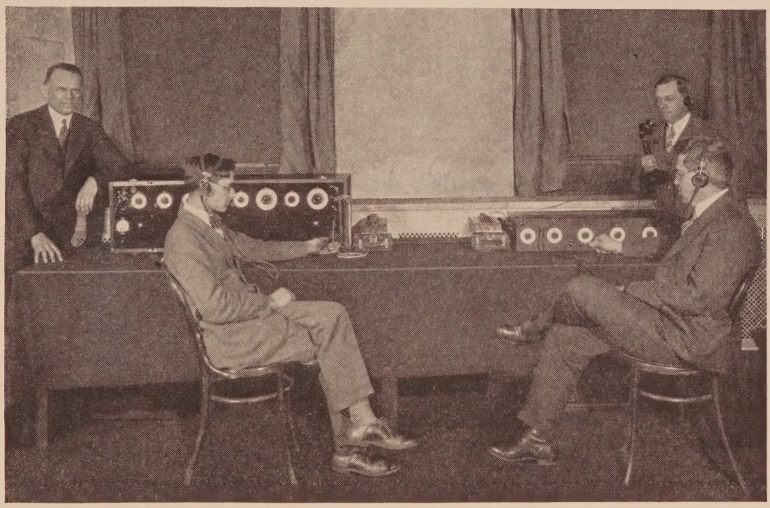


Fig. 5—Radio receiving equipment for the television and speech channels in the auditorium of Bell Telephone Laboratories, New York

The receiver employed at the New York terminus of the television channel presented a somewhat knotty problem on account of the relatively wide frequency band which it was required to pass while providing the maximum discrimination against interference. The width of the required band pointed very definitely toward the superheterodyne. This type of circuit is also very stable, permits of all the amplification that may be needed or that may be employed under ordinary noise conditions, and is very selective against interference immediately adjacent to the desired band. It is quite susceptible, however, to interference from components differing from the desired carrier frequency by an amount approximately equal to the intermediate frequency. If the interfering component lies in the neighborhood of the frequency of the oscillator, beats will be produced which

may or may not pass the intermediate-frequency amplifier and the associated filters depending on their design. If the interfering component lies on the opposite side of the wanted carrier from the oscillator and differs from the former by the intermediate frequency, it will be passed by the receiver, subject only to the attenuation due to the radio-frequency circuits (the input circuits tuned to the wanted

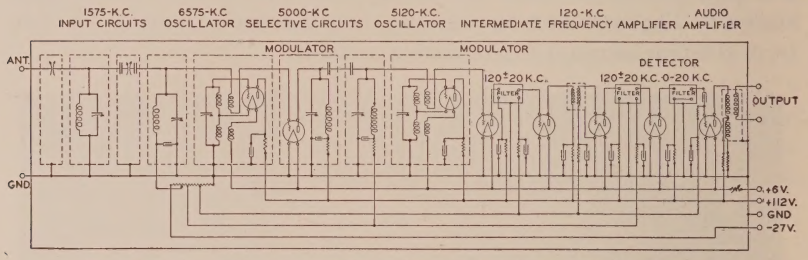


Fig. 6—Schematic of triple detection receiver for television channel

carrier). This characteristic must be given careful consideration in the design of selective receivers of the superheterodyne type and has led to the introduction of carefully designed, loosely coupled, input circuits or an initial tuned radio-frequency stage for this purpose. Neither of these expedients were possibilities in the television receiver, however, because of the extraordinary width of the required transmission band. Recourse was had, therefore, to a triple detection arrangement. Speaking somewhat in the vernacular, the desired signal was "beat up" to 5000 kilocycles where it was passed through sharply tuned coupled circuits, then "beat down" to 120 kilocycles, amplified, filtered and rectified, finally passing through a suitable low pass filter, audio amplifier and output transformer to the television reproducing apparatus.

The circuit arrangement is shown schematically in Fig. 6. Two tuned circuits with capacity coupling were connected to the input of the first detector or modulator. A relatively tight coupling was employed to produce the well-known double-peaked resonance curve capable of affording the required band width. The antenna was not tuned but was loosely coupled to the selective circuits by means of an adjustable capacity. The incoming radio signal was impressed upon the grid of the modulator tube along with a suitable voltage from an oscillator operating at 6575 kilocycles. The 5000-kilocycle components which resulted were selected by means of two carefully designed tuned circuits also capacity coupled. The purpose of this stage in the process will be evident if it is appreciated that at 1575

kilocycles, ± 20 kilocycles represents a 2.6 per cent band while at 5000 kilocycles the same side frequencies represent only a 0.8 per cent band. In the latter case, therefore, it is possible to employ materially sharper circuits without discriminating against the higher signal components. The 5000-kilocycle circuits connected to the grid of a second detector or modulator tube upon which suitable voltages from a 5120-kilocycle oscillator were impressed. The 120-kilocycle components in the output of this modulator were selected by means of a band-pass filter which worked into a two-stage intermediate-frequency amplifier. A second band-pass filter led to the third or final detector. A 20-kilocycle low-pass filter was employed in the plate circuit of the latter. This filter was designed for a low input impedance at 120 kilocycles in order to meet the necessary condition for efficient rectifier action and it also served as a coupling element for the audio stage which followed. A special output transformer with a permalloy core was provided to step down to the relatively low impedance of the line leading to the television apparatus proper.

A superheterodyne receiver of more conventional design was employed for the speech receiver. The circuit arrangement involved a double-tuned input circuit, one tuned radio-frequency stage, oscillator and modulator, two intermediate-frequency stages, detector and one audio stage. It was highly selective and afforded substantially distortionless transmission for signal frequencies ranging from 50 to 5500 cycles.

The transmitting equipment for the synchronizing channel consisted of a Western Electric 6-A Radio Broadcasting Transmitter modified to operate at 185 kilocycles. In order to avoid the necessity of transmitting directly the 17.7-cycle component required for synchronizing purposes, a 760-cycle carrier was modulated at 17.7 cycles by means of a relay and impressed upon the input of the radio transmitter together with the steady 2125-cycle component. At the receiving end, the 2125- and modulated 760-cycle components were separated by means of suitable filters, and the latter rectified to produce the desired 17.7-cycle current.

Tests of the System

As soon as the various apparatus units could be made ready for service, a comprehensive series of transmission tests was undertaken. In order to determine the relative suitability of the 1575- and 1750-kilocycle bands disclosed by the preliminary survey, transmissions from Whippany at intervals throughout the day were arranged. Field strength measurements were taken at the receiving point

employing apparatus of the type described by Englund and Friis[3] and observations on the relative strength of the received signals were made by inserting a sensitive microammeter in the plate circuit of the third detector of the television receiver. These data indicated that the lower frequency band suffered considerably less attenuation and also afforded much more stable transmission. In spite of the comparatively short distance (approximately 22 miles), marked fading was experienced beginning with the sunset period and increasing in amplitude as the night advanced. The high frequency band proved to be particularly disadvantageous in this respect. It was decided, therefore, to fix upon the lower frequency band and to confine the demonstration to the afternoon when reasonably stable transmission conditions prevailed.

Following the choice of a definite operating frequency, a number of modifications were made in the transmitting antenna to improve its efficiency and increase the field strength at the receiver. This work finally resulted in a measured field strength of approximately 2500 microvolts per meter for an antenna input of 5 kilowatts.

Further consideration of the available data on transmission and traffic conditions and the performance characteristics of the apparatus units involved lead to a choice of 1450 kilocycles for the speech channel. In spite of an antenna input of approximately 30 kilowatts, the initial tests at this frequency were very unsatisfactory due to inadequate field strength at the receiver which necessarily resulted in an abnormally high noise level. The height of the antenna was, therefore, increased from 60 to 100 feet by installing iron pipe topmasts. This change brought the field strength at the receiver to approximately the same value as that obtained for the television channel (2500 microvolts per meter) which was considered to be satisfactory for the purpose.

In order to insure that the reproduction of the picture might not suffer from serious discrimination against essential frequencies at some point in the radio system, very careful tests were made on the individual units and on the system as a whole.

The frequency characteristic of the transmitter was determined by connecting a vacuum tube oscillator producing a relatively pure wave to its input terminals through a suitable network involving a thermal milliammeter and an adjustable artificial line. A rectifier of known characteristics and a second thermal meter protected against radio-frequency currents by means of a low-pass filter were coupled to the

[3] "Methods for Measurements of Radio Field Strengths," C. R. Englund and H. T. Friis. Presented to the Spring Convention A. I. E. E. at Pittsfield, Mass., May 25, 1927.

output circuit of the water-cooled tubes. Employing a frequency of 1000 cycles, the input was adjusted to produce normal modulation and the readings of the input and output meters noted. The oscillator frequency was then changed by a convenient amount while holding the input reading constant and the artificial line readjusted, if necessary, to produce constant output current. Under these conditions, any change in the setting of the artificial line indicates an equal variation in the transmission efficiency of the transmitter which is evaluated by this method directly in TU.

The characteristic of the receiver was determined in a similar manner. A low power transmitter of known characteristics was connected to it through a suitable attenuating network which, in so far as the receiver was concerned, simulated the receiving antenna. The radio-frequency input to the receiver was adjusted to approximately the normal value and a series of measurements taken with variable audio-frequency inputs as indicated above.

The overall measurements were also based on a similar procedure impressing a constant input on the 600-ohm input terminals of the transmitter through a suitable artificial line and adjusting the latter to give a constant current into a 600-ohm load at the output of the receiver, taking necessary precautions, of course, to preclude overloading at any point in the system.

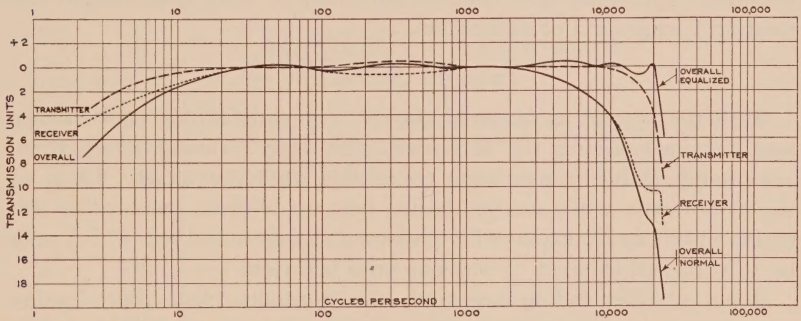


Fig. 7—Measured characteristics of television channel

The experimental characteristic curves thus obtained are shown in Fig. 7, where the abscissæ represent cycles per second and the ordinates departure from the 1000-cycle value in TU. As will be noted, at the lower frequencies exceptionally good performance was obtained, the overall characteristic being only 2 TU down (or deficient) at 10 cycles and only 6 TU down at 3 cycles. The results for the higher frequencies, however, were not so satisfactory, a loss of approximately

13 TU being observed at 20,000 cycles, probably due to the tuned circuits in the receiver. Since modification of these circuits to obtain a flatter characteristic would have been difficult and would have occasioned a noteworthy sacrifice in selectivity, a compensation network was designed for use in the 600-ohm output circuit of the receiver which introduced a negligible loss at 20,000 cycles, a substantially constant loss of 13 TU at frequencies below 2000 cycles, and for intermediate frequencies losses represented by the height of the "normal overall" curve above the horizontal line representing — 13 TU. With this network connected between the receiver and the television equipment, the average level throughout the band was, therefore, reduced some 13 TU but the resulting characteristic as measured beyond the network was that which has been designated "overall equalized." Above 20,000 cycles the characteristics all fell very rapidly which is an indication of the degree of selectivity attained. This was contributed to by the radio-frequency tuned circuits, the band-pass filters in the intermediate-frequency amplifier and the 20,000-cycle low-pass filter between the final detector and audio amplifier. The individual characteristics of the various filters were designed to be 60 TU down 20 kilocycles from the specified cut-off frequency.

Similar measurements were made upon the speech channel but a less thorough study was deemed sufficient in that case due to the existing background of experience.

Effects of Fading

With the system as outlined above, very satisfactory performance was obtained during the afternoon and early evening hours when reasonably stable transmission conditions were prevalent. Later at night, however, when marked fading became evident, some rather unexpected but easily explainable phenomena were observed which may be of sufficient interest to warrant brief mention.

When marked fading occurred, the normally clear reproduction was accompanied by "ghosts" or additional images which faded in and out in an erratic manner, sometimes appearing as positives and sometimes as negatives. The effect was most clearly observed when using one of the various types of test screens employed, a white card bearing a black diamond-shaped outline, approximately a square with its diagonals vertical and horizontal. With this simple type of pattern, it became evident that the secondary images were additional reproductions which were "out of frame" by a greater or less amount. In other words, each of these additional images consisted of a portion

of two diamonds placed side by side with the corners just touching. Images "out of frame" along the vertical axis are frequently seen on the motion picture screen.

The explanation is fairly obvious. The present more or less generally accepted view of fading is that it is a manifestation of transmission along two or more paths, at least one of which is variable, producing a continually changing phase relationship between the components and a corresponding waxing and waning of the resultant signal. In the present case, the major image was probably produced by the so-called "ground wave." The secondary images probably resulted from components which were transmitted upward at a relatively sharp angle and turned back to the receiving station from the Heaviside layer, the difference in framing being due to the longer time of transmission.

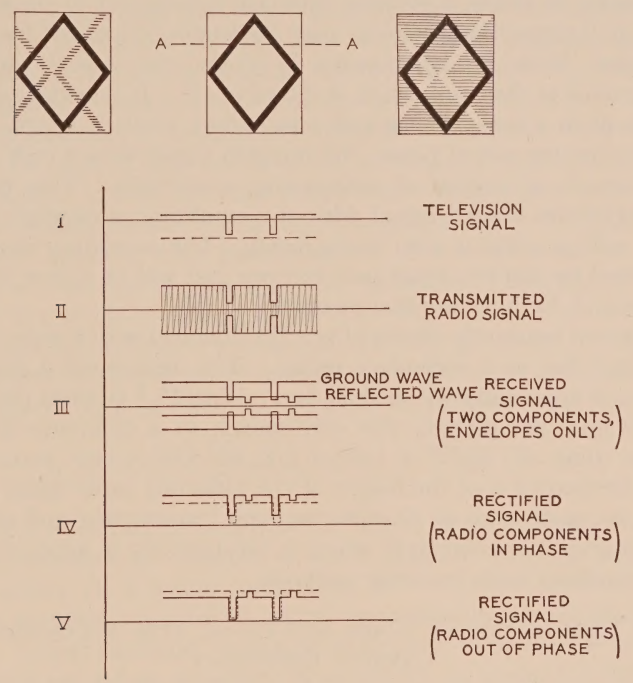


Fig. 8—Production of positive and negative secondary images due to multi-path transmission

The production of negative secondary images is a most interesting phase of the phenomena. This effect may be explained quite easily by means of a series of signal diagrams such as is shown in Fig. 8.

If attention is confined to the interval during which scanning takes place along the line AA, it is evident that the television signal will have the form shown. Amplitudes above the dotted line indicate the current through the photoelectric cell. Since transformer-coupled amplifiers are employed in the television apparatus, however, the direct component is eliminated and the zero axis for the input to the radio transmitter is the solid line. Sketch II shows the modulated output of the radio transmitter. The received signal, shown in III, is assumed to consist of two components, the larger due to the "ground wave," and the smaller due to reflected energy from the Heaviside layer. The latter lags somewhat because of the greater length of the transmission path. The resultant of these two components will necessarily depend on the relative phase of the two carriers at the receiving point. Two cases are considered: when the components are exactly in phase, and when they are exactly out of phase. The effect at intermediate positions may be readily evaluated from these examples. With the components in phase, the detector output is proportional to their sum which is shown in IV. It is evident that this will result in a major image and a secondary positive image. If the components are out of phase, the rectified signal shown in V results. It is simply a matter of subtracting amplitudes. This resultant consists of the desired signal with the amplitude somewhat reduced which will produce a gray background. The secondary image will be formed by the two small peaks shown and will be lighter than the background, in other words a negative.

A pattern frequently observed was the diamond with a cross through its center due to a secondary image. This represents a change in framing of approximately one half line. With 17.7 pictures per second and 50 lines per picture, this corresponds to a difference in transmission time of $1/17.7 \times 1/50 \times 1/2$ or 5.65×10^{-4} seconds. A rough computation of the height of the reflecting layer based on this figure and a distance of 22 miles between transmitting and receiving stations gives 100 kilometers, which is substantially in agreement with determinations made by other methods.

Transmission of Voice and Image with a Common Carrier Frequency

Following the demonstration, a brief series of supplementary tests was arranged to obtain some appreciation on experimental grounds of the problems involved in transmitting both voice and image with a single radio transmitter. The system employed may be considered as the extension of carrier current technique to radio, but has been

described in various other terms: "multiplex radio," "double modulation," "the Hammond system," etc. The output of a 30,000-cycle oscillator was modulated with the speech signal. The resulting carrier and sidebands were selected by means of a suitable filter passing frequency components ranging between 25,000 and 35,000 cycles and impressed on the input terminals of the radio transmitter along with the 10 to 20,000-cycle signal from the television apparatus. A suitable low-pass filter was employed in the line to the latter in order to preclude "crosstalk" due to 25,000–35,000-cycle energy working back into the final amplifier stages. The input to the radio transmitter thus consisted of a band extending from 10 to 20,000 cycles together with a 25,000 to 35,000 band, with a particularly strong component at 30,000 cycles representing the low-frequency carrier.

In order that it might be capable of handling this wider band without discrimination, further modifications in the radio transmitter were required. In the case of some of the radio-frequency circuits, which were required to pass a 70,000-cycle band, it was found to be necessary to insert resistance to reduce the sharpness of resonance. On account of lack of time, it was not possible to obtain a complete series of characteristic curves for the transmitter under these conditions. Isolated measurements with a single-frequency input of 35,000 cycles indicated, however, that components of this order could be transmitted without serious loss and the subsequent performance of the system as a whole confirmed this conclusion.

It is well known that if a sinusoidal alternating current $i = I_0 \sin \omega t$ is modulated with a signal of frequency $f = \Phi/2\pi$, the resulting modulated current may be represented by the expression:

$$i = I_0 \sin \omega t + \frac{kI_0}{2} \sin (\omega + \Phi)t + \frac{kI_0}{2} \sin (\omega - \Phi)t,$$

where k is a fraction indicative of the degree of modulation. In other words, a modulated current, or wave, may be resolved into three components: (1) a steady component, known as the "carrier," which has the amplitude and frequency of the original unmodulated current, (2) an "upper sideband" which is equivalent to the signal spectrum with each individual frequency increased by an amount equal to the carrier frequency, and (3) a "lower sideband" which is an inverted reproduction of the signal spectrum, that is, each individual signal component is laid off in the downward direction from the carrier frequency, or subtracted from it. Hence, assuming a carrier frequency of 1575 kilocycles and a signal input to the radio transmitter

of the type described above, the antenna current, or the transmitted wave, may be represented diagrammatically as shown in Fig. 9.

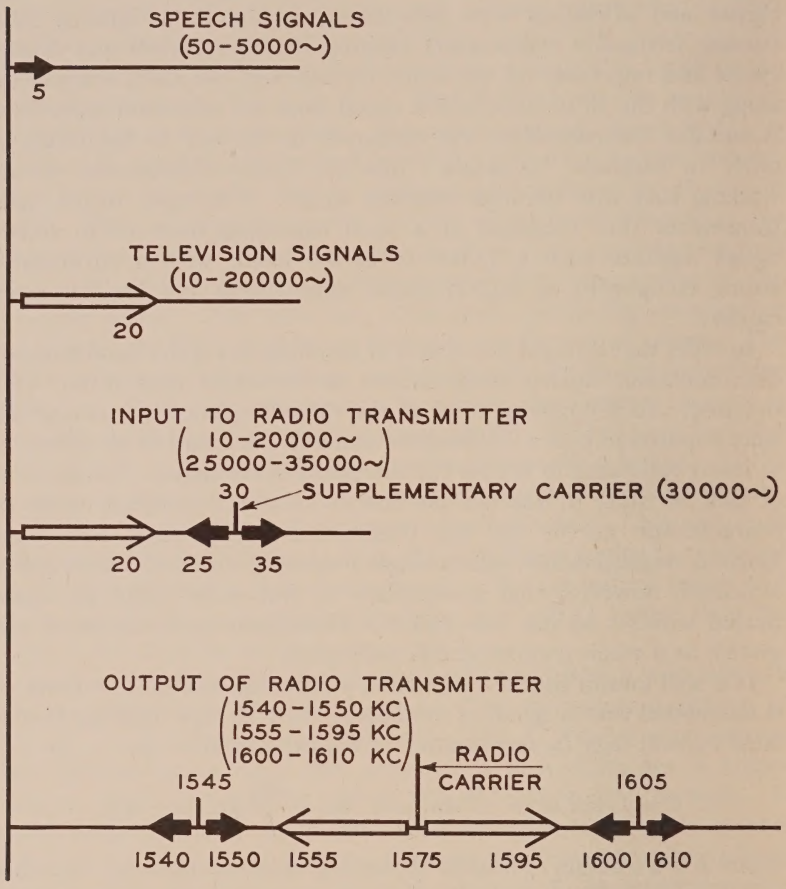


Fig. 9—Diagrammatical representation of frequency conversions in multiplex radio system

It is evident that this type of radio signal can be received by employing an arrangement which will accept the entire band and subject it to rectification in the usual manner. If this is done, the television signal and the 30,000-cycle supplementary carrier modulated with speech will appear at the output of the detector. Branch circuits with suitable filters will enable these two components to be separated and the television signal passed on to the reproducing apparatus. The

other component must be rectified to derive the original speech signal, which may then be impressed on the loud speaker amplifiers.

The reception scheme actually employed during the experiments was somewhat different. The television signal was received separately by means of the triple detection set employed for the demonstration. The speech signal was received in a similar manner employing the set utilized for the speech channel during the demonstration. This latter receiver was tuned to 1545 kilocycles. That reception in this manner is feasible, is evident from the diagram. The 1540–1550-kilocycle zone contains two speech sidebands and a carrier of 1575 — 30 or 1545 kilocycles. It is quite possible, therefore, to demodulate in one step, instead of "beating" the various components against the main carrier (1575 kilocycles) to produce a 30-kilocycle supplementary carrier which must be rectified a second time to derive the speech signal. The 1600–1610-kilocycle band was ignored. The receivers were sufficiently selective that, with the 5-kilocycle interval which existed between the two bands, no noteworthy crosstalk was experienced.

The results obtained in this manner were not as satisfactory as those to be had with the other system described. This can be attributed to two factors, both concerned with the transmitting apparatus: (1) In order to transmit both signals with the same transmitter, that is, the same vacuum tubes, the individual current amplitudes had to be reduced to at least one half, resulting in too weak a radio signal to clear the prevailing noise levels in New York, (2) In spite of the reduced amplitudes, a certain amount of inter-modulation was experienced in the transmitter which resulted in "crosstalk" between the channels. Notwithstanding these deficiencies, however, it was possible to recognize the speaker and to understand his remarks; but a short time ago, the performance would have been considered a very noteworthy achievement.

Experiments of this nature, although not new, are of particular interest where television is concerned, since, as Dr. Ives has indicated, the logical trend of development is toward a finer picture structure involving the transmission of much wider frequency bands, or what is more likely, the use of parallel scanning schemes and multi-channel transmission. The work, while necessarily somewhat cursory, may, therefore, be of value in affording an indication of the significance of multi-channel radio transmission in this connection. From a popular standpoint, these tests have been described as the transmission of both voice and image "on a single wave-length." To what extent this statement falls short of actually representing the facts in the case is

obvious from Fig. 9. It will be seen that a wider frequency band is actually employed with this system than was required for two separate channels. Furthermore, this wider band is much less effectively utilized. Two bands are required for the voice channel in place of one. At the receiver, one of these bands was disregarded. To have received both would have required apparatus accepting twice the band width and the gain in signal would have been offset by the corresponding increase in noise level. For all useful purposes, therefore, the energy radiated in the form of the second band is wasted.

To proceed further with a discussion of multi-channel radio transmission is beyond the scope of the present paper. Whatever the system employed, however, one conclusion illustrated by these experiments may be pointed to with confidence: television by radio requires a discrete and fairly wide frequency band. Hence the frequently predicted introduction of television as an adjunct to radio broadcasting without extensive changes in existing channel arrangements is extremely unlikely.

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